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CIRCULAR PIEZOELECTRIC BENDER LASER TUNERS

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CIRCULAR PIEZOELECTRIC BENDER LASER TUNERS

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ABSTRACT

The circular piezoelectric bender laser tuner can replace conventional laser tuners when mirror diameters up to 0.50 inch (1.27 cm) are sufficient. The circular piezoelectric bender laser tuner offers much higher displacements per applied volt and permits laser control circuits to be fabricated using standard operational amplifiers, rather than the expensive high-voltage amplifiers required by conventional tuners. The circular bender tuner provides a displacement per volt factor of up to 0.125 μm/volt, in comparison with a typical 7.5×10^{-3} μm/volt factor for a conventional tuner. The cost of the device is more than one order of magnitude lower than conventional tuners and the device is very rugged with all mechanical resonances easily designed to be greater than 3 kHz. In addition to its use as a laser frequency tuner, the circular bender tuner should find many applications in interferometers and similar devices.

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ILLUSTRATIONS

ILLUSTRATIONS (continued)

CIRCULAR PIEZOELECTRIC BENDER LASER TUNERS

1. INTRODUCTION

1.1 General Design Considerations

Laser frequency tuning is often accomplished by mounting one of the laser's mirrors on a piezoelectric element. There are three types of piezoelectric tuners in common use: disks, cylinders, and stacks of disks. The purpose of this report is to describe the characteristics of a fourth type of piezoelectric tuner, the circular piezoelectric bender, which has a number of features making it superior to other tuners for some applications. The theory of the piezoelectric bender will be discussed with respect to deflection and resonant frequency and the theoretical results will be compared with experimental data on two designs for mounting the bender. The first design discussed is for an internal mirror laser and the second is for an external mirror laser.

The work described in this report was prompted by the need to develop a piezoelectric tuner for spaceborne CO_2 laser communication systems.[1] Evaluating the requirements of those systems led to the desired characteristics listed in Table I. The required tuning range was dictated by the expected thermal environment of the spacecraft and the need to minimize the number of times frequency stabilization would be lost. The considerations involved in selecting the required tuning range are described elsewhere.[2]

Table I

Desired Piezoelectric Tuner Characteristics

Tuning Range	0 to 15 μm Minimum
Mass	Minimized
Structure	Rigid and Compact
Tuning Voltage	Minimized, Less Than Several Hundred Volts for 15 μm Travel
Thermal Sensitivity	Expansion of device and variation of other parameters with temperature should be negligible over a range of 20 ±15°C.
Aging Characteristics	Device properties should not change over a two year or greater period.
Length	Minimized to reduce laser cavity length.

1.2 Characteristics of Standard Piezoelectric Tuners

The simplest tuner is a single disk employed as shown in Figure 1. The change in thickness as a function of applied voltage for an unloaded, unclamped disk is given by

$$\Delta x = d_{33} \, \Delta V \tag{1}$$

where d_{33} is the piezoelectric coefficient relating the change in crystal thickness along a given axis to the voltage applied along the same axis. Table II gives the values of d_{33} for a number of piezoelectric materials available from Gulton Industries[3] and Clevite Corp.[4] Table II also gives values for d_{31}, the coefficient relating the change in crystal length along a given axis to the voltage applied along a perpendicular axis.

It is evident from Eq. (1) and Table II that a simple disk tuner cannot meet the requirements of low operating voltage and 15-μm translation simultaneously, as given in Table I.

The voltage requirement can be reduced by using a piezoelectric cylinder as shown in Figure 2. The free translation due to the applied voltage is

$$\Delta x = d_{31} \frac{L}{T} \Delta V \tag{2}$$

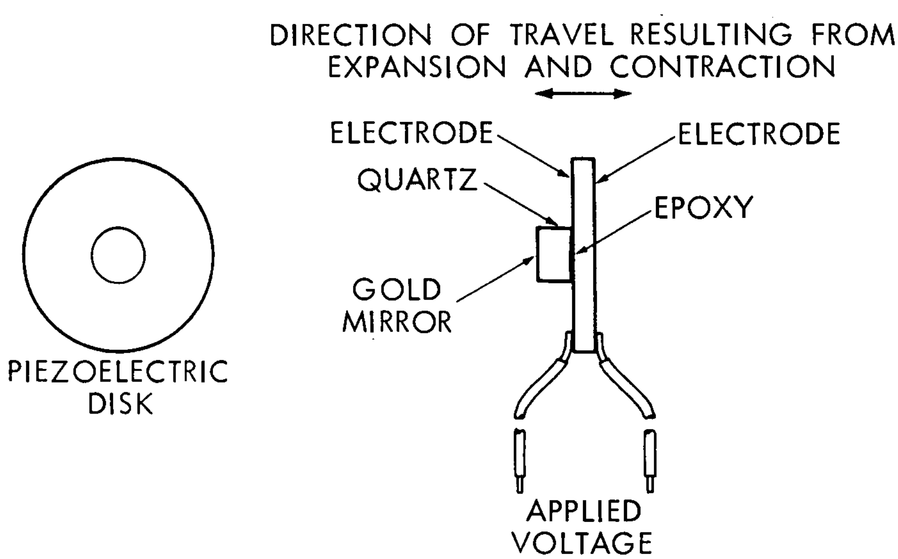

Figure 1. Piezoelectric Disk Tuner

Table II

Characteristics of Representative Piezoelectric Materials

Material	d_{33} (meters/volt)	d_{31} (meters/volt)
HS-21	148×10^{-12}	-50×10^{-12}
HST-41	325×10^{-12}	-157×10^{-12}
G-1408	200×10^{-12}	-80×10^{-12}
G-1500	370×10^{-12}	-166×10^{-12}
G-1512	500×10^{-12}	-232×10^{-12}
PZT-4	285×10^{-12}	-122×10^{-12}
PZT-5	374×10^{-12}	-171×10^{-12}
PZT-5H	593×10^{-12}	-274×10^{-12}

where L is the length of the cylinder and T is the wall thickness. A typical cylinder might have a length of 7.62 cm (3 inches) and a wall thickness of 0.508 cm (0.2 inch). Therefore, a travel of 15 micrometers requires an applied voltage of no less than 3650 volts. The high voltage requirement and the length of the device rule it out.

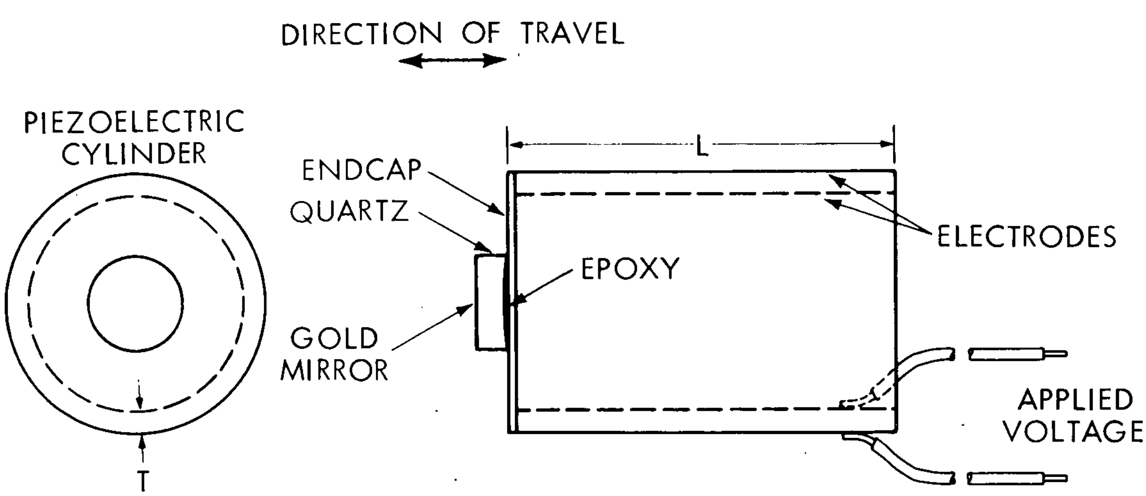

Figure 2. Piezoelectric Cylinder Tuner

A third approach is a stack of parallel-connected piezoelectric disks, as shown in Figure 3. Devices with 50 or more disks should be feasible, with the expansion of each disk governed by Eq. (1). Compactness requires that the individual disks be relatively thin, which in turn limits the maximum usable voltage. With most materials the nominal voltage limit is 10 to 15 volts/mil, due to a gradual depoling of the material which occurs under the application of higher fields. A representative stack used by the authors consists of 25 active and 2 inactive layers, each of which is 2.54 cm (1 inch) in diameter and 0.0508 cm (0.020 inch) thick. The stack was constructed using the G-1512 material listed in Table II and has a length of 1.4 cm (0.55 inch). The maximum permissible applied voltage is 300 volts positive and 200 volts negative, which leads to a displacement of 0.0125 μm/volt or 6.25 μm maximum travel. Additional disks could be added at the cost of length and difficulty of fabrication to increase the deflection to 15 μm. The length, probable high cost, and anticipated reliability problems rule out this approach.

2. THEORY OF THE CIRCULAR PIEZOELECTRIC BENDER

A circular piezoelectric bender is constructed by bonding together two plates of piezoelectric material polarized in opposite directions such that, when a voltage is applied, one plate expands radially (increases in diameter) and the other contracts. This causes the bender to "dimple" in the center. The unloaded, unclamped deflection of a circular bender is approximated by the equation[5]

$$\Delta x \cong \frac{3}{8} d_{31} \frac{D^2}{T^2} \Delta V \tag{3}$$

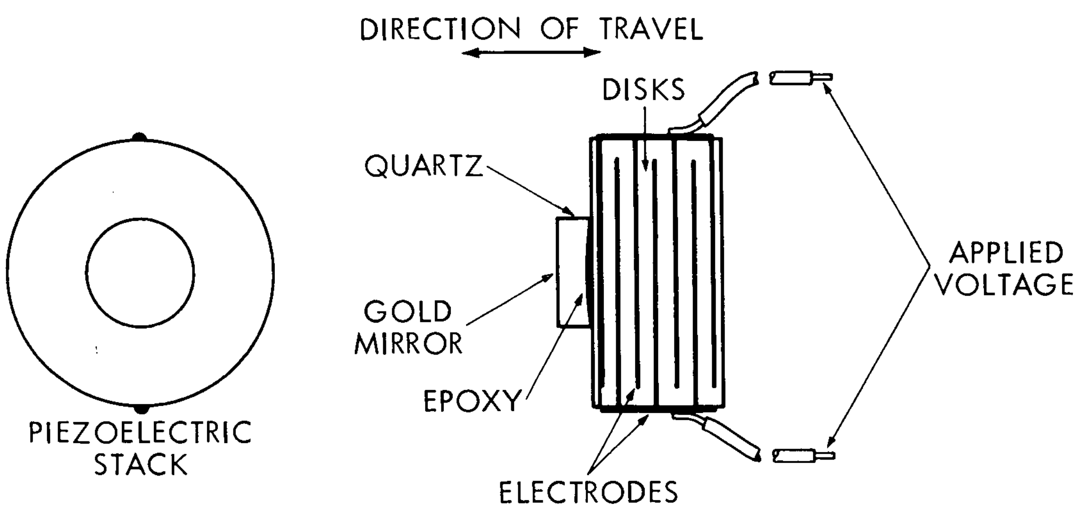

Figure 3. Piezoelectric Stack Tuner

where D is the diameter and T is the thickness. This equation, in practice, gives the maximum displacement which can be obtained. It assumes that the slope of the bender at the clamped surface (usually a concentric ring on the perimeter) is not constrained. Because most mounting techniques, with the possible exception of a thin knife-edge support ring, constrain the slope of the bender, the obtainable deflection is less than that given by Eq. (3). The exact computation of deflection is made exceedingly difficult by the uncertainties in the characterization of the mounting forces and method of mirror attachment. No general analysis has been found which gives a closed form solution. The accuracy of Eq. (3) has been verified as shown in the following sections.

The same difficulties complicate the calculation of the resonant frequency. For that reason, the only equation which has been found to be of practical value gives the resonant frequency as

$$f_r \cong \frac{\Omega^2}{2\pi} \frac{T}{a^2} \left(\frac{E}{12\,\rho}\right)^{1/2} \tag{4}$$

where Ω is the eigenvalue occurring in the solution of the differential equation for a vibrating circular plate, a is the bender's radius, E is Young's modulus, and ρ is the density.[6] For a free, unloaded plate, Ω^2 is nominally 9.0, while an unloaded plate clamped on the perimeter has a value of nominally 10.0. These values, when inserted in Eq. (4), give a rather coarse approximation of the expected range for the resonant frequency. This will be evident in the following section on the experimental results.

3. EXPERIMENTAL RESULTS

3.1 Tuner Mounting Designs

Two approaches were taken to the design of a suitable mounting for the circular piezoelectric bender laser tuner. The first design was developed for use with an internal-mirror, flowing-gas, CO_2 laser. This design is shown in Figure 4. The bender is clamped between two opposing circular rings. The left-hand ring in the figure is made of aluminum and serves as the ground connection to the tuner. The right-hand ring is constructed from Delrin® and insulates the mounting frame from the tuning voltage, which is applied to a lead epoxied to the rear electrode. Silver coatings are fused to both sides of the bender providing a uniform electrode on both surfaces.

The adapter plate mounts, through an O-ring seal, against the end of a precision-ground Cervit® block[7] which serves as a low thermal coefficient of expansion mirror separator. A vacuum by-pass equalizes the pressure on both

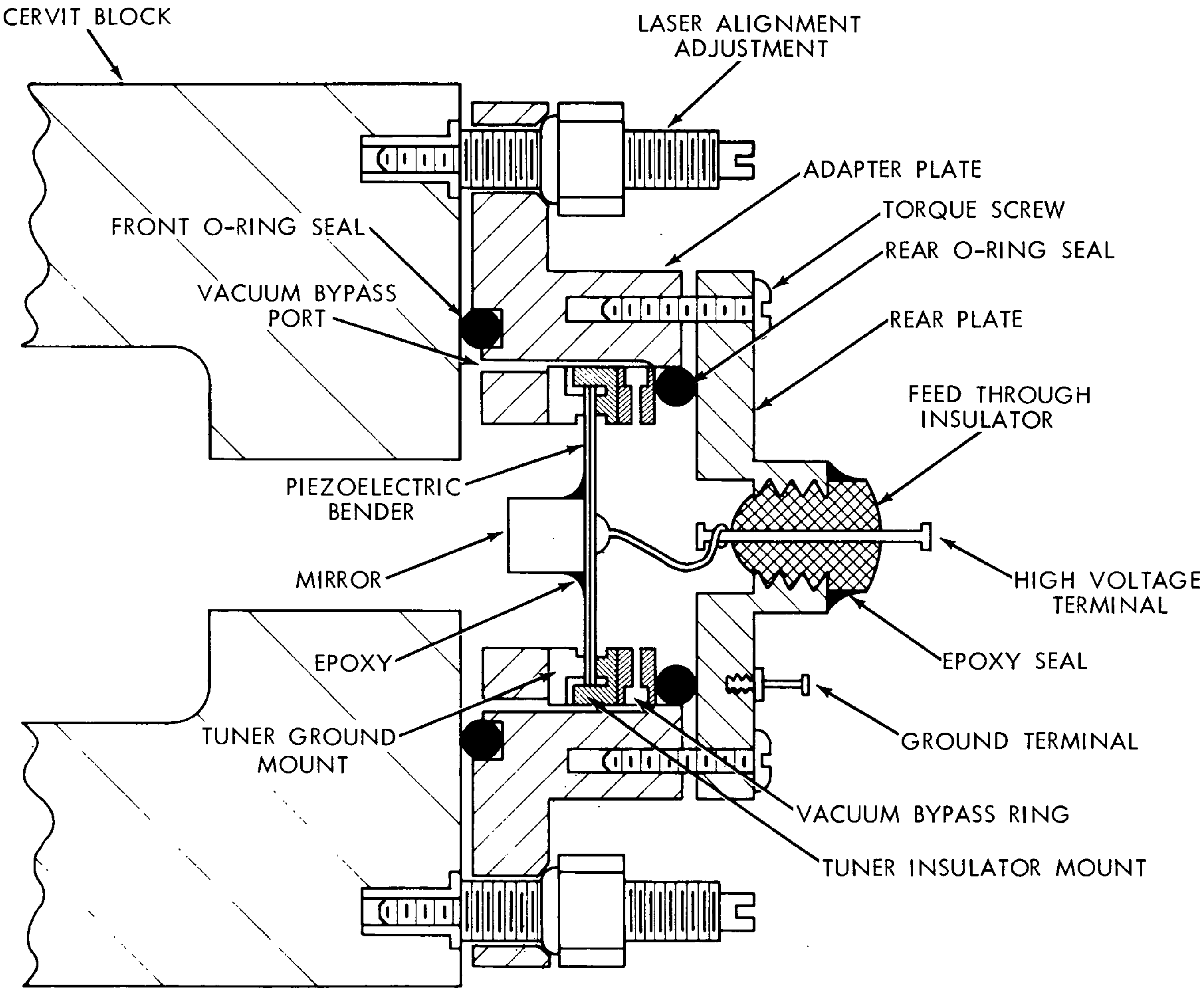

Figure 4. Configuration used for Internal Mirror Laser (Mounting "A")

sides of the tuner. Compression of the front O-ring seal provides for sufficient adjustment to align the laser and compression of the rear O-ring seal is used to vary the clamping pressure. Figure 5 shows the disassembled tuner, Figure 6 shows a close-up view of the tuner installed on the laser, and Figure 7 shows an overall view of the laser and tuner.

The second tuner mounting design is for an external mirror laser and is shown in Figure 8. The tuner is held in a Delrin® insulating ring by a stainless steel ground ring. As in the preceding design, the tuner voltage is applied to the back surface of the tuner by means of a lead fastened with conducting epoxy to the silver electrode. Pressure is applied to the bender directly in this design, rather than through an O-ring seal as in the previous design. Locking screws operating at right angles to the adjustment screws hold the mirror position after initial alignment of the laser. Laser alignment is facilitated by an alignment fixture which screws into the rear of the tuner holder. The two spherical mating surfaces provide a high degree of rigidity and resistance to misalignment. A mirror mount of this type has passed the qualification vibration test cycle for the Titan-IIIC launch vehicle. A second mount of this type required no adjustment over a period of 12 months in spite of extremely rough handling, including four flights on a high-altitude research balloon, each of which terminated in a parachute drop from 50,000 to 90,000 feet. After the 12-month period, no readjustment was necessary, but the tuner was removed and disassembled for other tests. Figure 9 shows the disassembled mirror mount, Figure 10 shows the assembled mount, and Figure 11 shows the mirror mount installed in the unit which was flown on the research balloon. The laser and its associated circuits are described in another report.[8]

3.2 Displacement Measurements

Gold-coated quartz mirrors of various sizes were epoxied in two ways to circular piezoelectric benders and the displacement was measured as a function of applied voltage, type of mounting, and clamping pressure. In Mounting "A" (Figure 4), the tuner was mounted between two rings of varying widths centered at a radius of 0.4375 inches (1.11 cm). Rings of widths 0.080 inch (0.20 cm), 0.040 inch (0.10 cm), 0.020 inch (0.051 cm), 0.010 inch (0.025 cm), and a knife-edge were tested. A calibrated torque wrench was used to vary the pressure applied by the mounting clamps to the tuner. Values of 8 in-oz (0.056 nt-m), 16 in-oz (0.11 nt-m), 24 in-oz (0.17 nt-m), 32 in-oz (0.23 nt-m), and 40 in-oz (0.28 nt-m) were employed. In Mounting "B" (Figure 8), the tuner was mounted between two rings of fixed width. The stainless-steel ground ring has an outer diameter of 0.985 inch (2.502 cm) and a width of 0.055 inch (0.14 cm). The insulating ring has an inner diameter of 0.987 inch (2.507 cm) and a shoulder width of 0.036 inch (0.091 cm). In most measurements 1-inch (2.54 cm) diameter

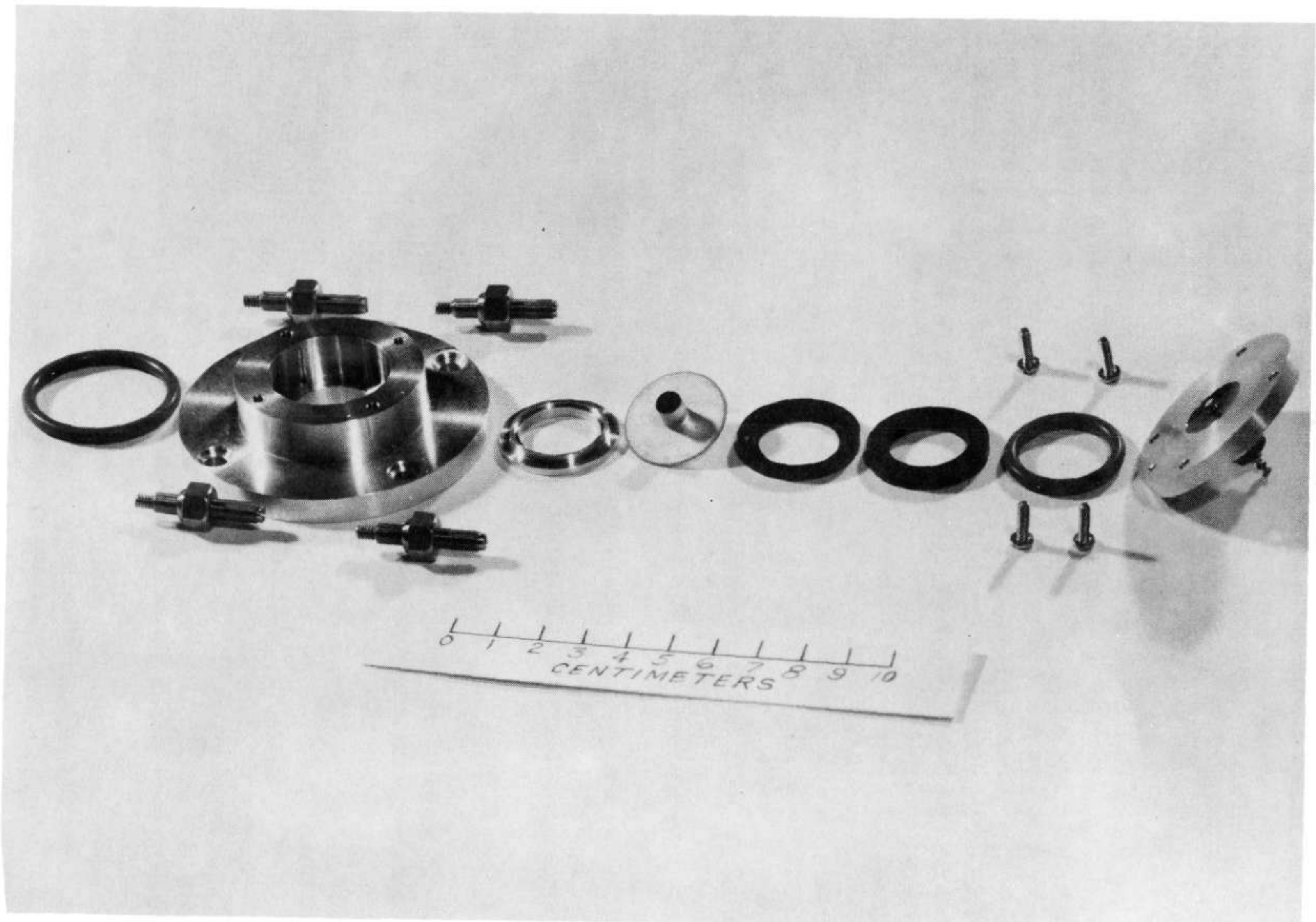

Figure 5. Disassembled Tuner

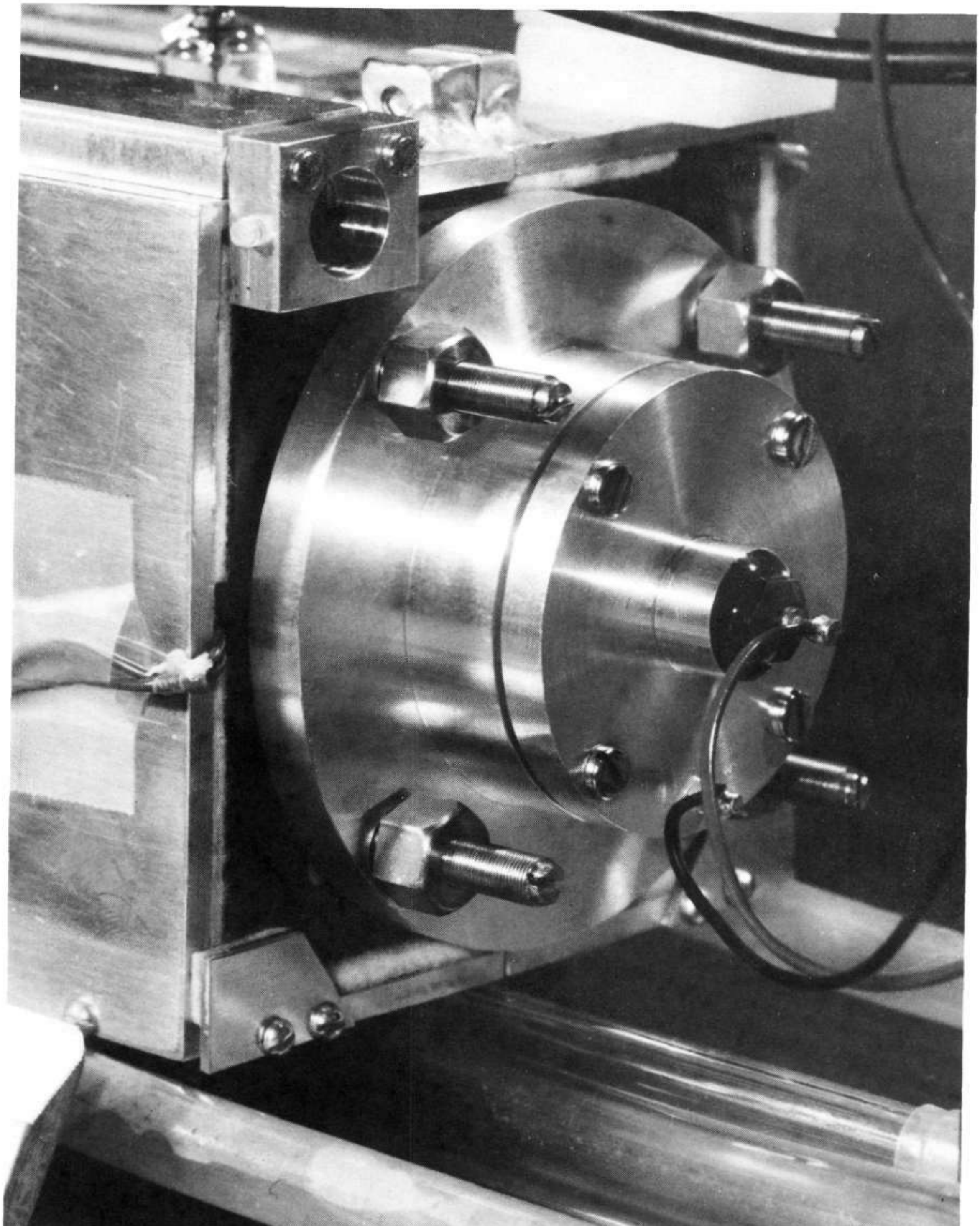

Figure 6. Close-up View of the Tuner Installed on the Laser

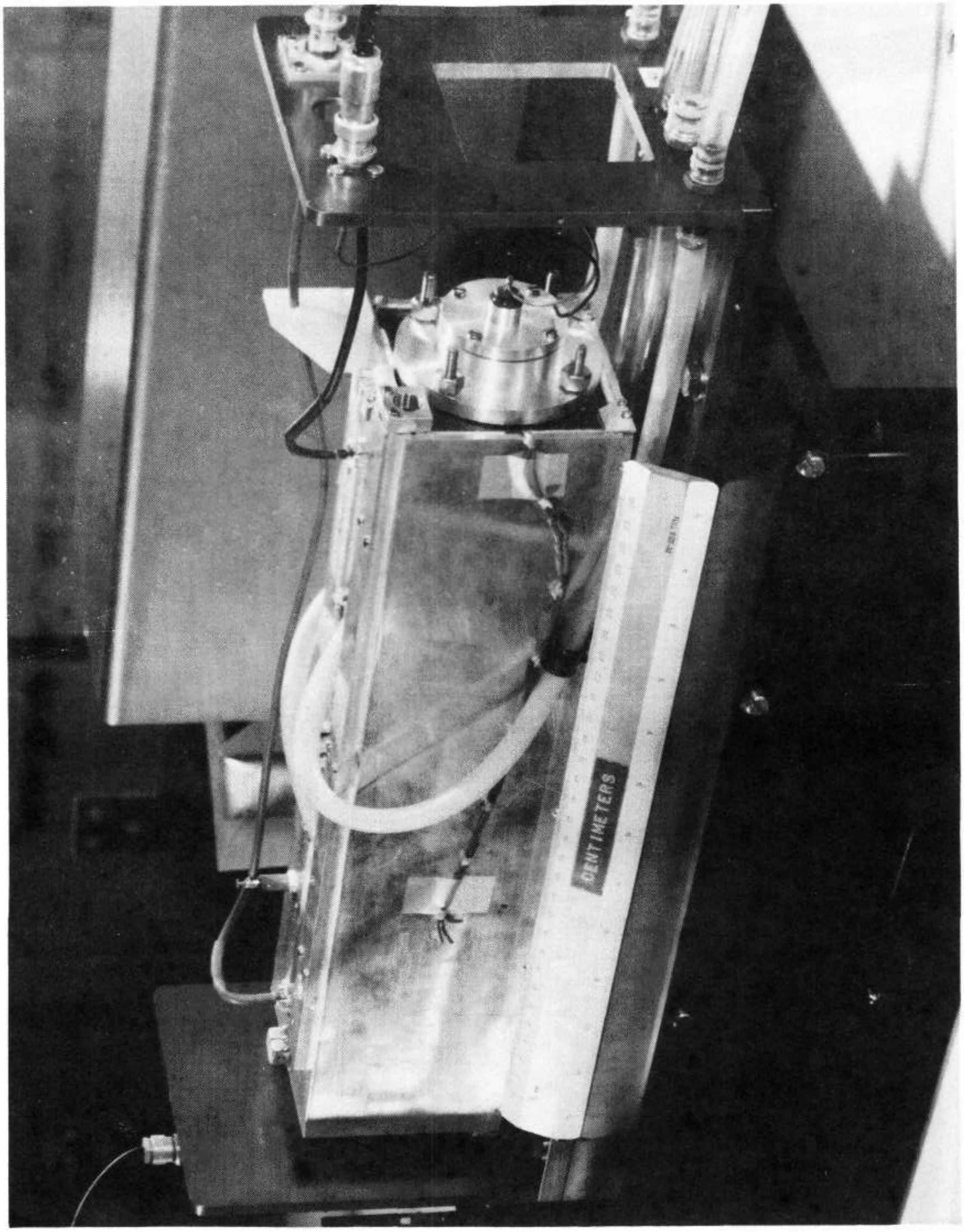

Figure 7. Overall View of the Laser and Tuner

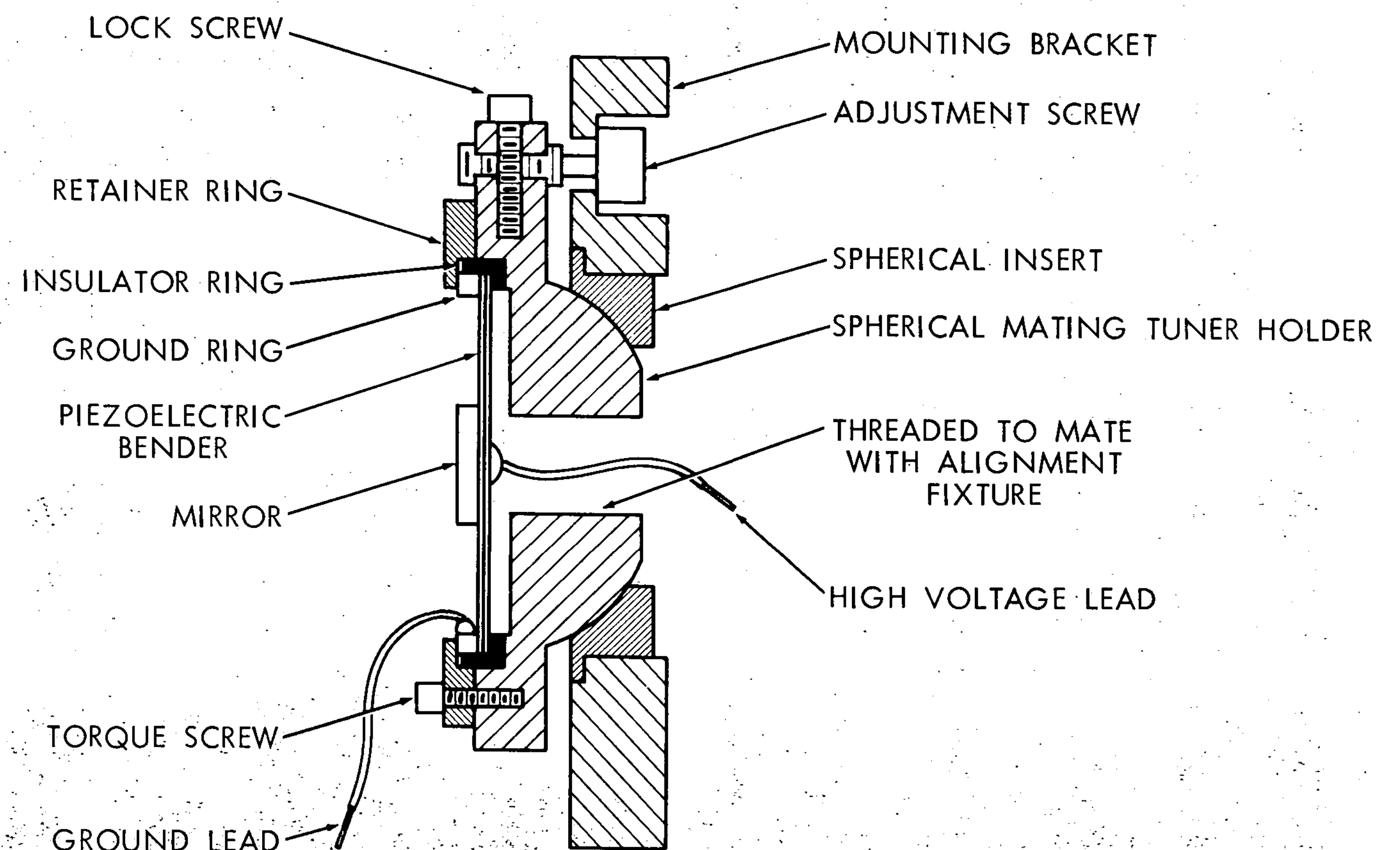

Figure 8. Configuration for External Mirror Laser (Mounting "B")

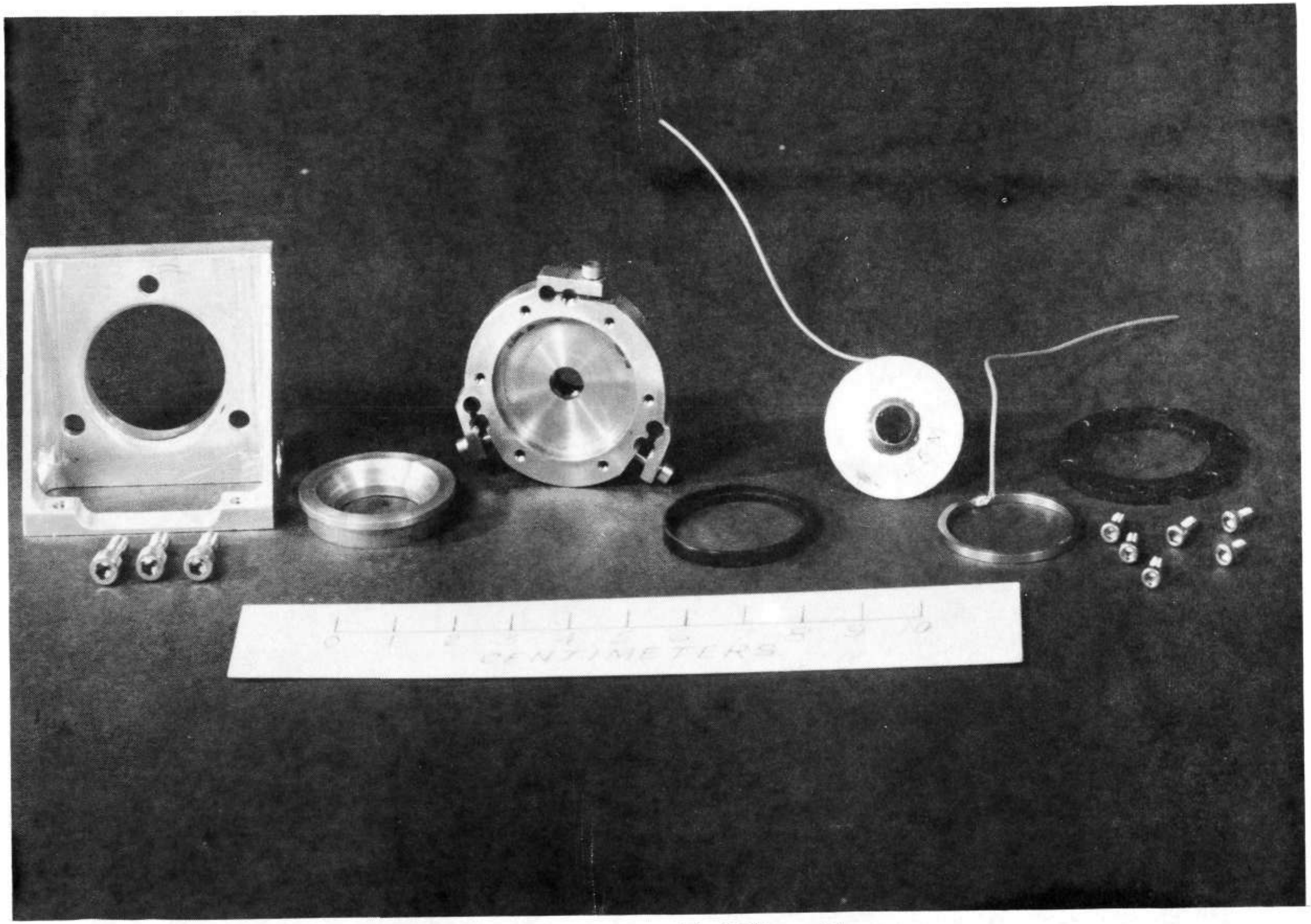

Figure 9. Disassembled Mirror Mount

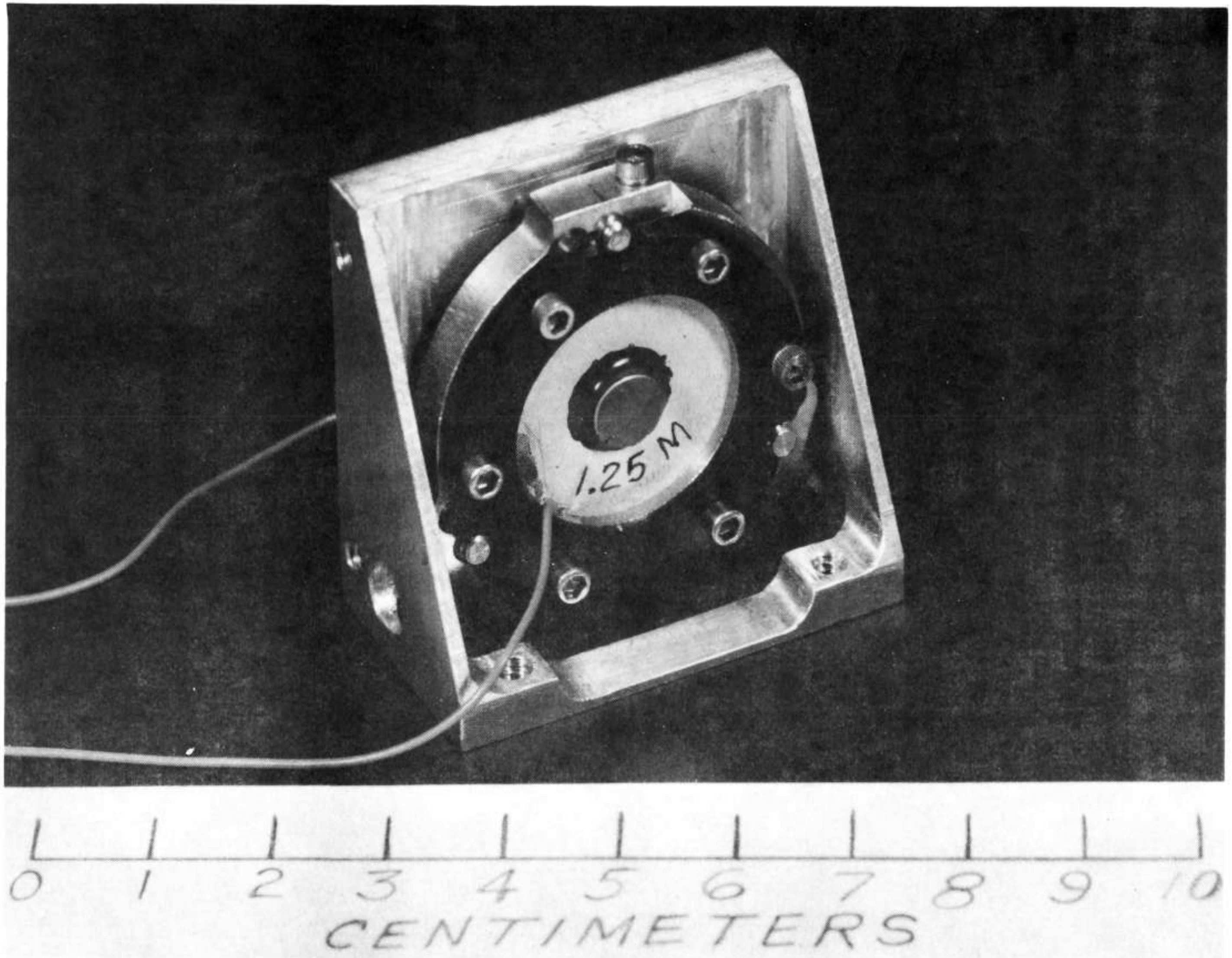

Figure 10. Assembled Mirror Mount

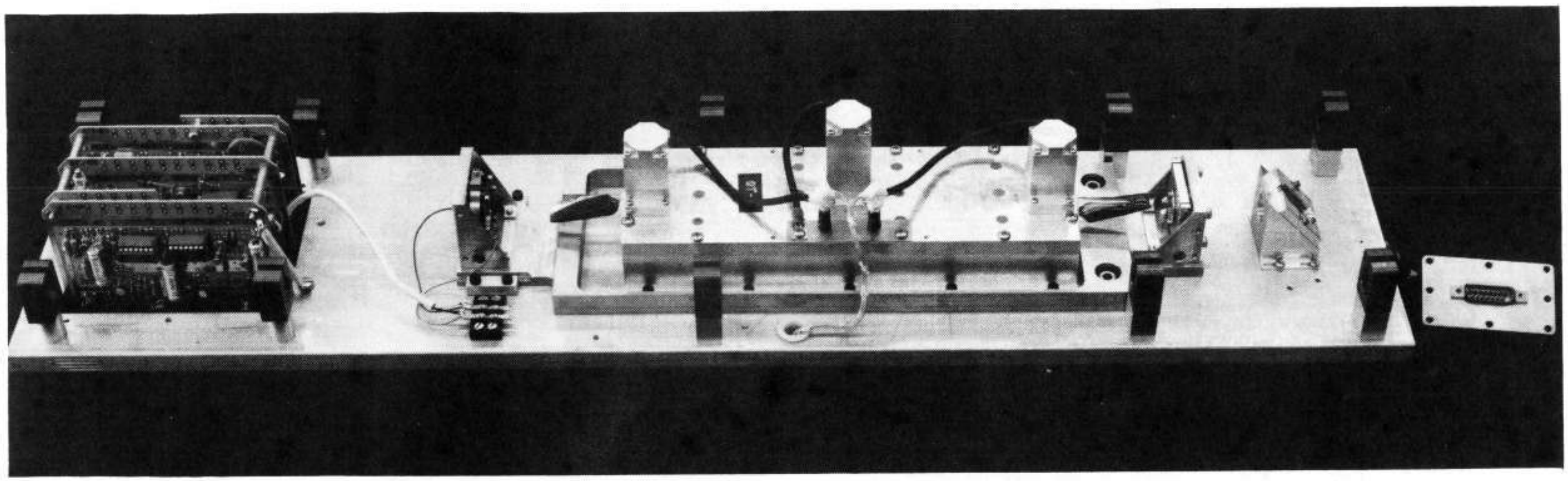

Figure 11. Mirror Mount Installed

HST-41 epoxy-bonded circular benders were used. The benders have a density of 7.6 gm/cm^3 or larger, a Young's modulus of 7.0 x 10^{10} $nt\text{-}m^2$, and a thickness of 0.020 inch (0.051 cm).[3] With this thickness, applied voltages of up to 300 volts could be used.

Measurements were also made on a similar bender fabricated in a "monolithic" structure. This type of bender is made from two 1-inch (2.54 cm) diameter, 0.010 inch (0.0254 cm) thick disks of G-1512 material bonded together by a high temperature fusion process which eliminates the use of epoxy. Besides being able to withstand much higher temperatures, this type of bender has the added advantage of being machinable to accurate tolerances after assembly. The benders tested had a 0.125 inch (0.318 cm) diameter hole machined in the center over which the mirror was placed for attachment with a semi-pliable epoxy. Figure 12 shows a diagram of the bender with a 0.5 inch (1.27 cm) diameter mirror attached. Since final grinding can be done after the disks are bonded together, the silver electrodes can be made to extend all the way to the edges of the bender, while in the epoxy bonded benders the electrodes stop nominally 0.030 inch (0.0762 cm) from the edge.

The test set-up used for both displacement and resonant frequency measurements on the epoxy-bonded benders is shown in Figure 13. The switch below the tuner is shown in the proper position for displacement measurements. A variable dc driving voltage is used, after amplification, to sweep the tuner through its range. The voltage applied to the tuner was varied between ±300 volts. The output from the laser was directed to two detectors. The first detector measured the signature of the laser[9] and the second detector, at the output slit of a monochrometer set for the P(20) line of the CO_2 laser, identified the half-wavelength displacement points in the signature. By tuning the laser through successive half-wavelengths and measuring the voltage at which each P(20) line occurs, a plot was generated of the displacement of the tuner as a function of applied voltage. Figure 14 shows a photograph of the test set-up used with epoxy-bonded benders in Mounting "A"; the set-up for Mounting "B" was identical except for the laser. The measurements on the "monolithic"

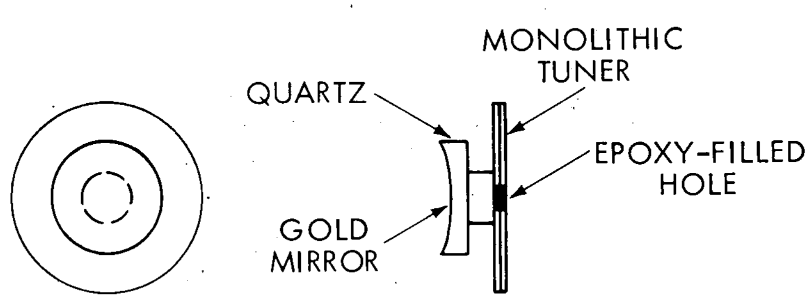

Figure 12. Monolithic Bender Tuner

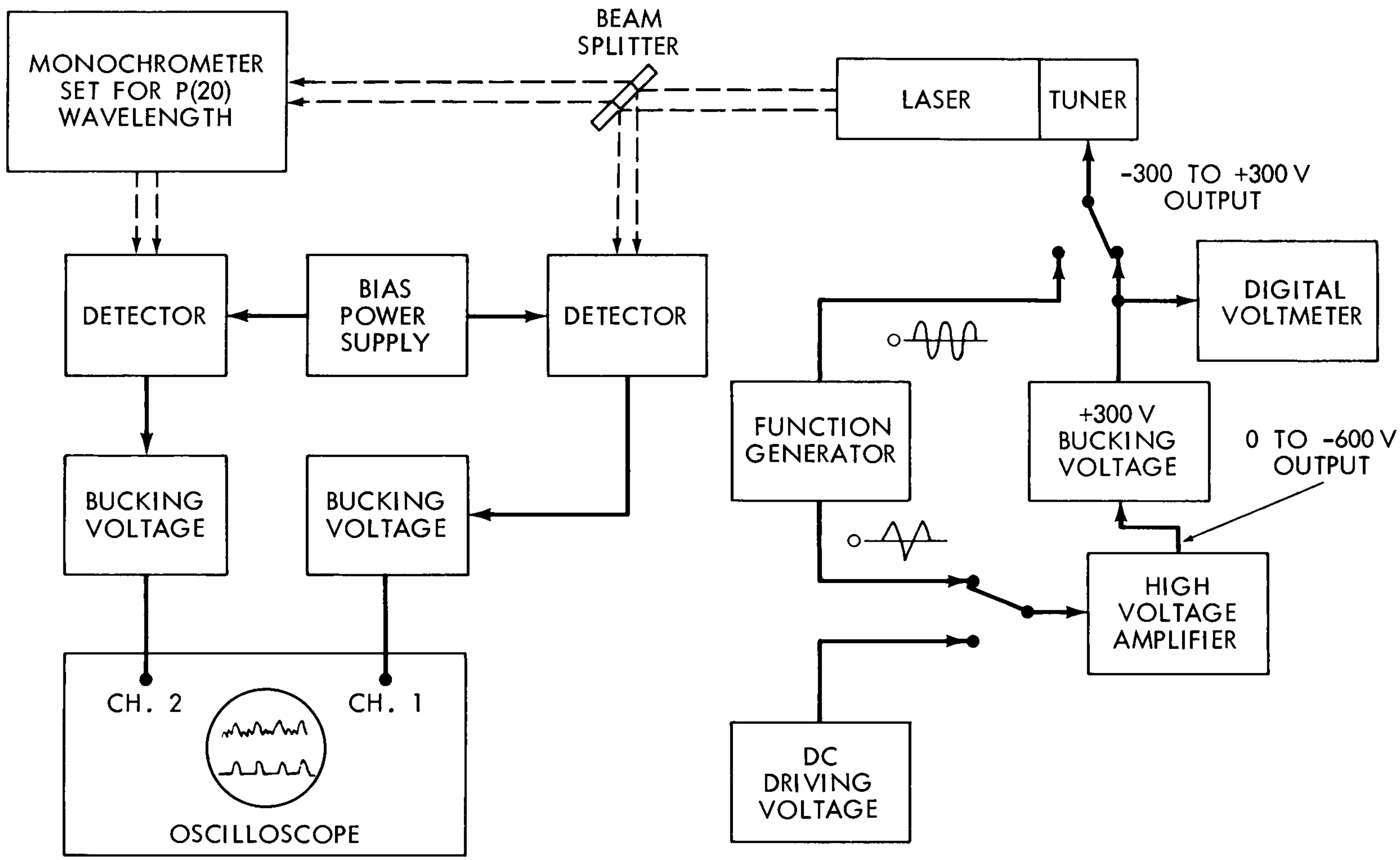

Figure 13. Test Set-up

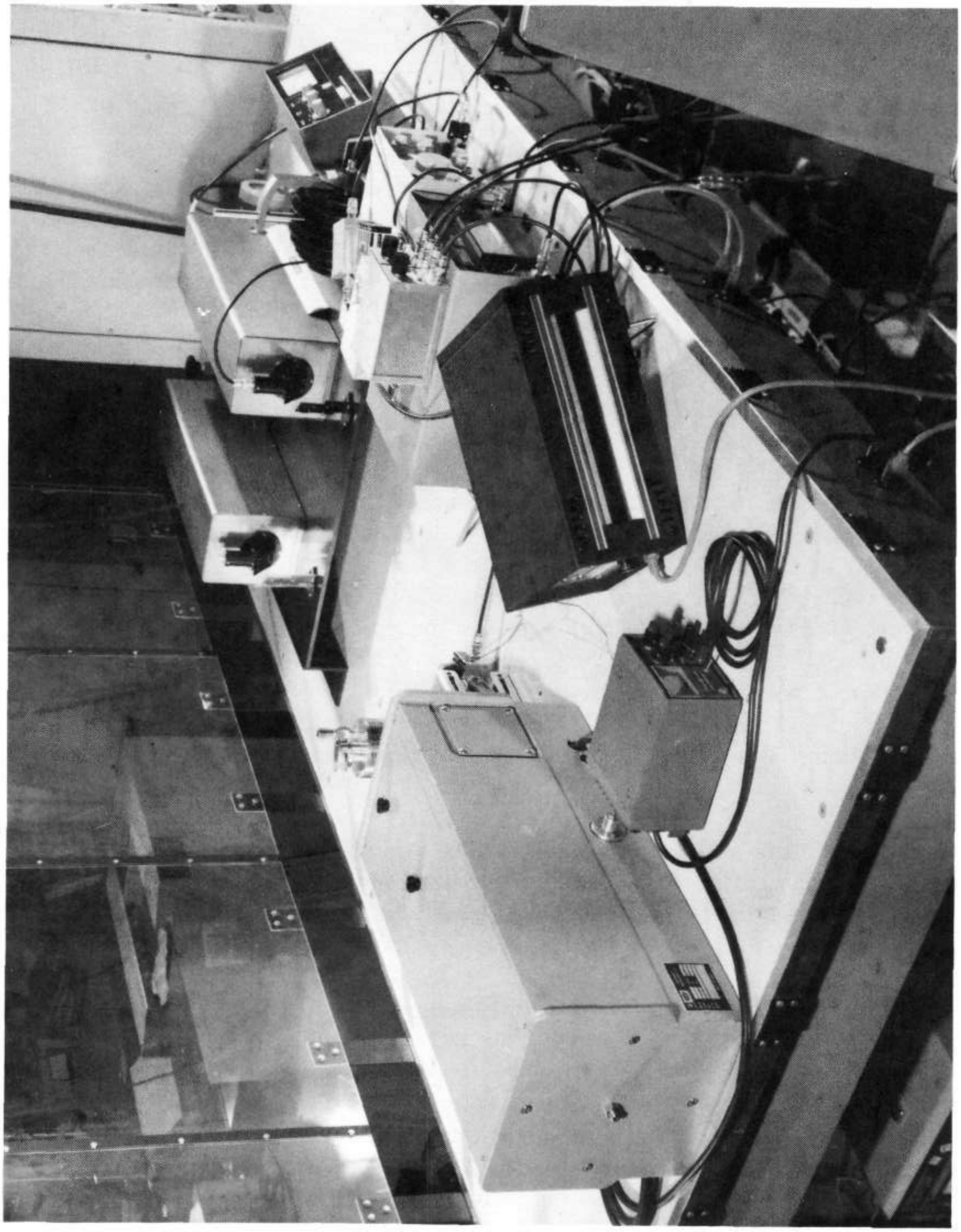

Figure 14. Test Set-up used with Epoxy-bonded Benders in Mounting "A"

benders were performed with a Fizeau interferometer operating at 5460 Å by counting fringes.

Figures 15, 16, and 17 show the experimental results obtained with a 0.318 cm thick, 0.7 cm diameter quartz mirror for three widths of clamping rings and several torque values applied to the clamping screws in Mounting "A". It can be seen that the displacement varies from 68 μm with a lightly clamped knife-edge to nominally 16 μm for a firmly clamped 0.051 cm clamping ring. A particularly noticeable feature of the experimental data is the pronounced hysteresis. In each case, the lower of the two curves associated with a given torque value represents the curve traced for increasing applied voltage, while the upper curve is for decreasing applied voltage. Figures 18, 19, and 20 show data obtained with a larger mirror.

The manner in which the mirror is epoxied to the tuner can have a pronounced effect on the available displacement. This is evident in Figures 21 and 22. Two mirrors of approximately the same size were attached differently to two tuners to demonstrate this effect. Only the ascending portion of the hysteresis curve is shown in order to make the comparison more evident. In Figure 21, the rear surface of the mirror was ground slightly spherical and a single drop of epoxy used to attach the mirror to the tuner. In Figure 22, a filet of epoxy was built up around the edge of the mirror to attach it to the tuner. The effect of the greater stiffness resulting from the epoxy filet is clearly indicated from the nominal 20 μm reduction in travel. Both Figures 21 and 22 show data taken with an epoxy-bonded bender in Mounting "B". The mounting technique shown in Figure 12 for the "monolithic" bender using a pedestal and a machined hole for the epoxy is an approach to minimizing the mirror contact area and the resulting stiffening of the transducer.

Examining Figures 15 through 22 leads to the conclusion that the variation in mirror size has little or no effect on the available travel. Figure 23 shows data taken to determine if the tuner could be used with a much larger mirror than any previously used, but without the precautions of using the technique shown in Figure 12 to mount the mirror. It can be seen that a mirror of this size does produce a significant loading effect on the tuner's performance.

Although the displacement versus voltage curve is clearly non-linear for large voltages, it is very close to linear over small voltages. This can be seen in Figure 24, which shows that a "monolithic" tuner constructed from the G-1512 material and firmly clamped in Mounting "B" is quite linear over a 5 μm range. Figure 25 shows data for the same tuner and mounting over a larger voltage range and the resulting deviation from linear performance. To test the stability of the device, a voltage of 150 volts was applied to the device for two weeks and

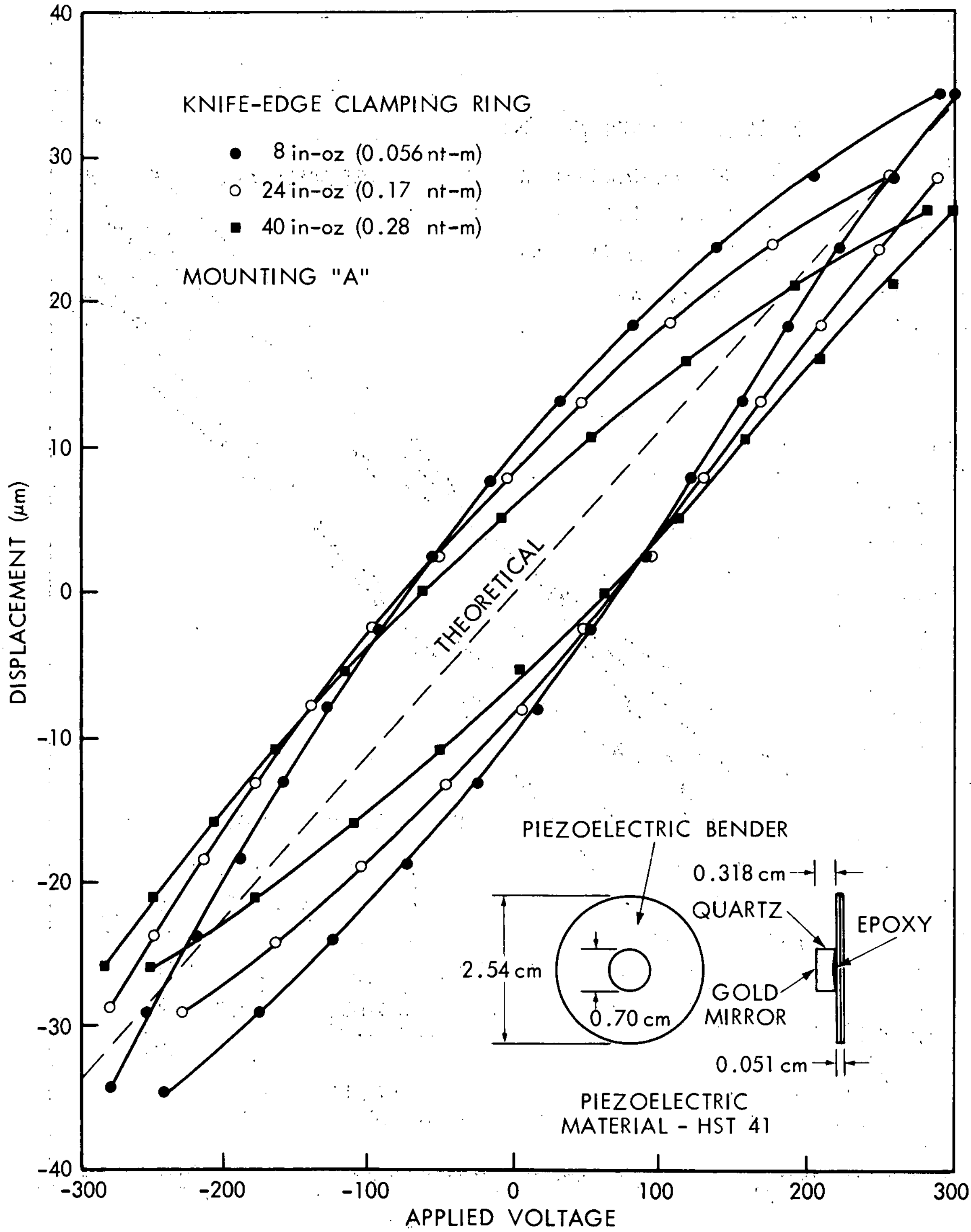

Figure 15. Experimental Results, Knife-Edge Clamping Ring (Mounting "A")

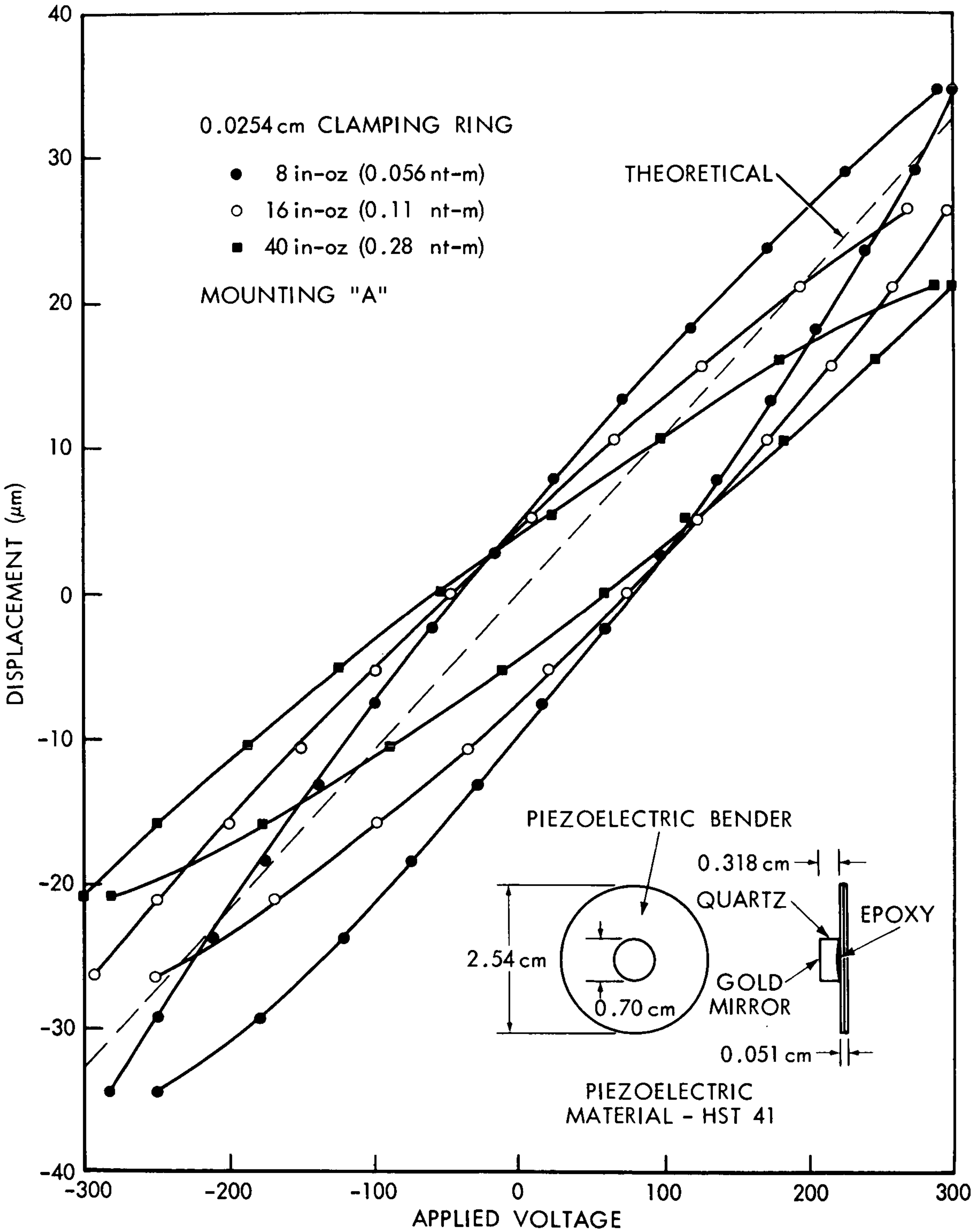

Figure 16. Experimental Results, 0.0254 cm Clamping Ring (Mounting "A")

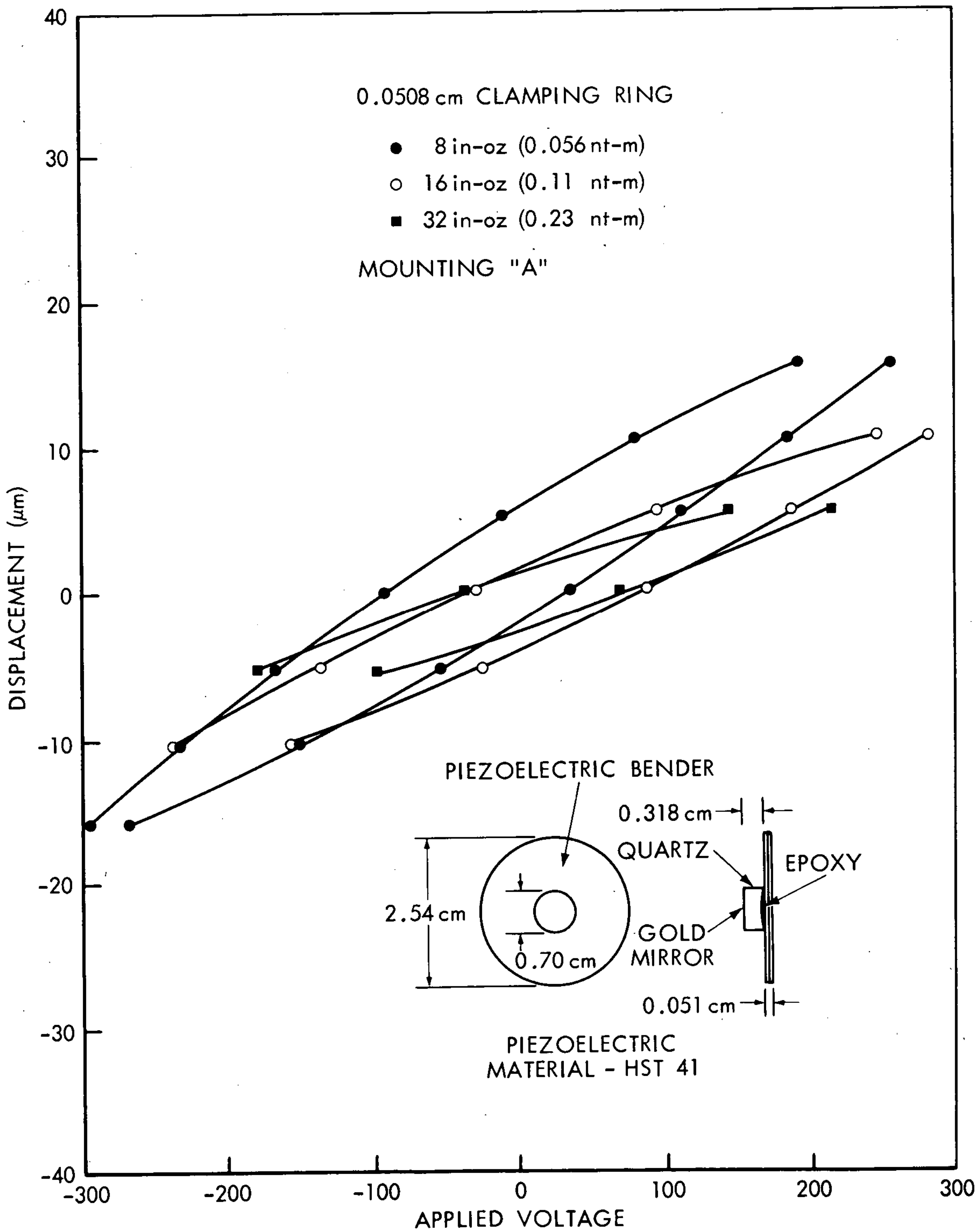

Figure 17. Experimental Results, 0.0508 cm Clamping Ring (Mounting "A")

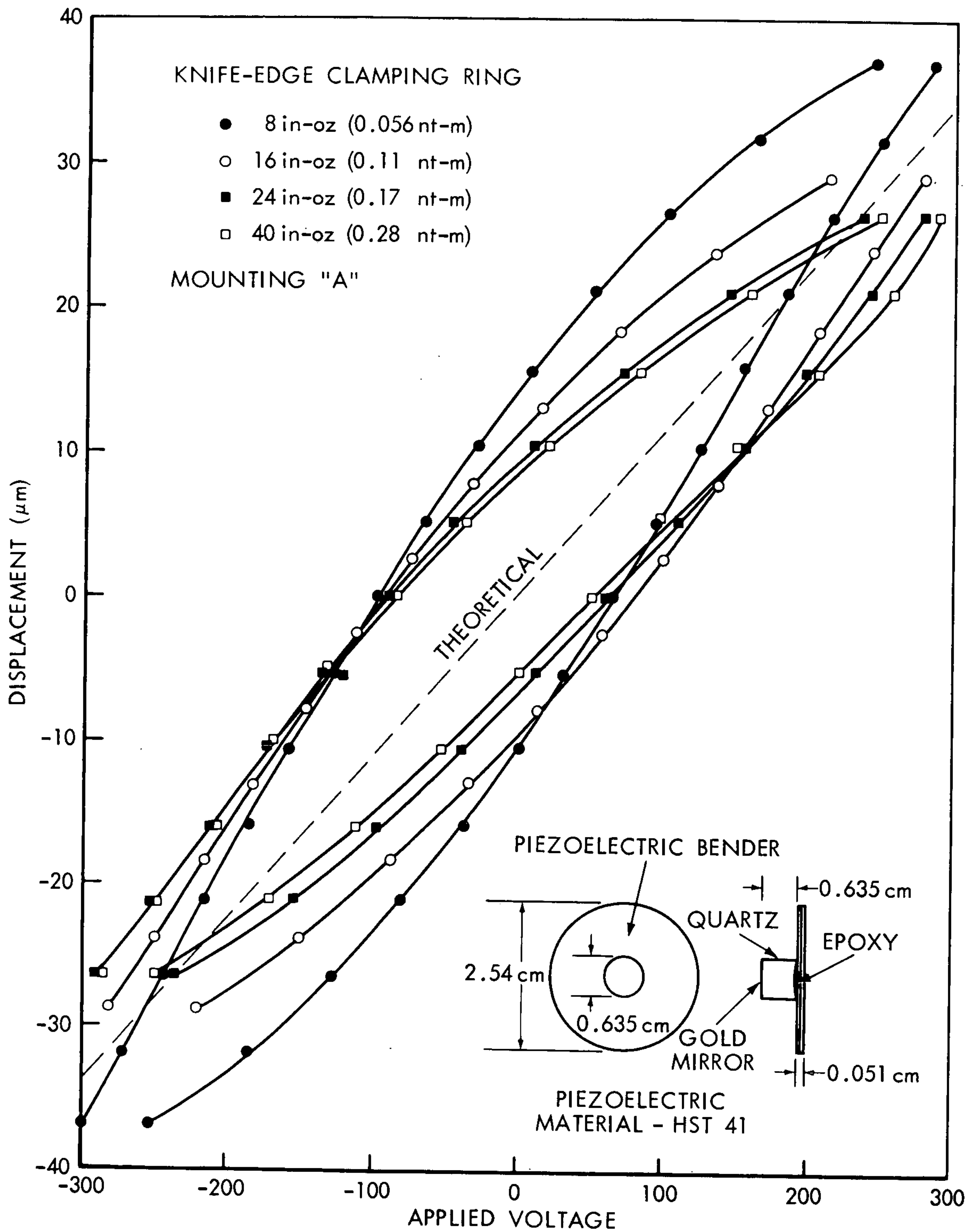

Figure 18. Data Obtained with a Larger Mirror - Kinfe-Edge Clamping Ring

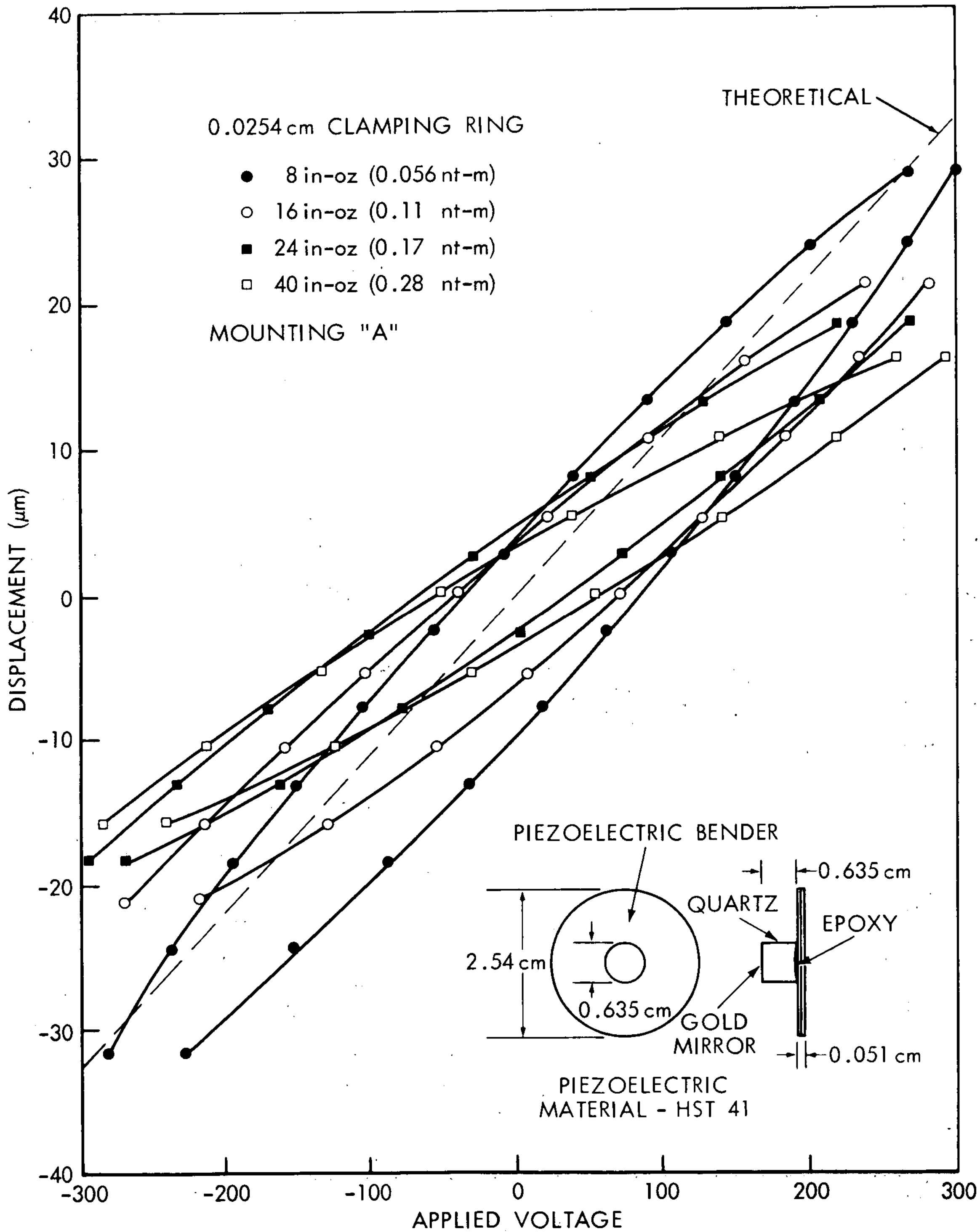

Figure 19. Data Obtained with a Larger Mirror - 0.0254 cm Clamping Ring

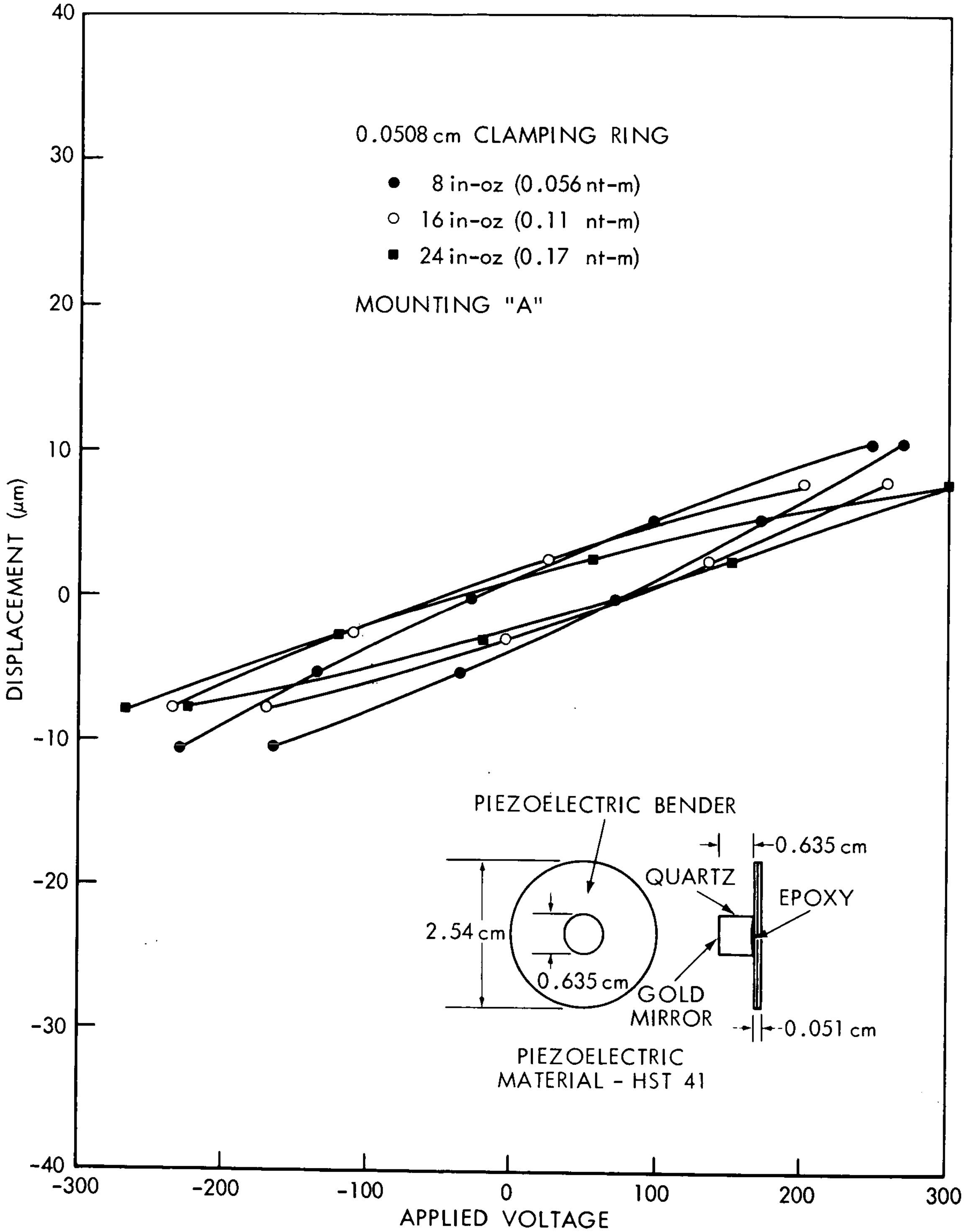

Figure 20. Data Obtained with a Larger Mirror - 0.0508 cm Clamping Ring

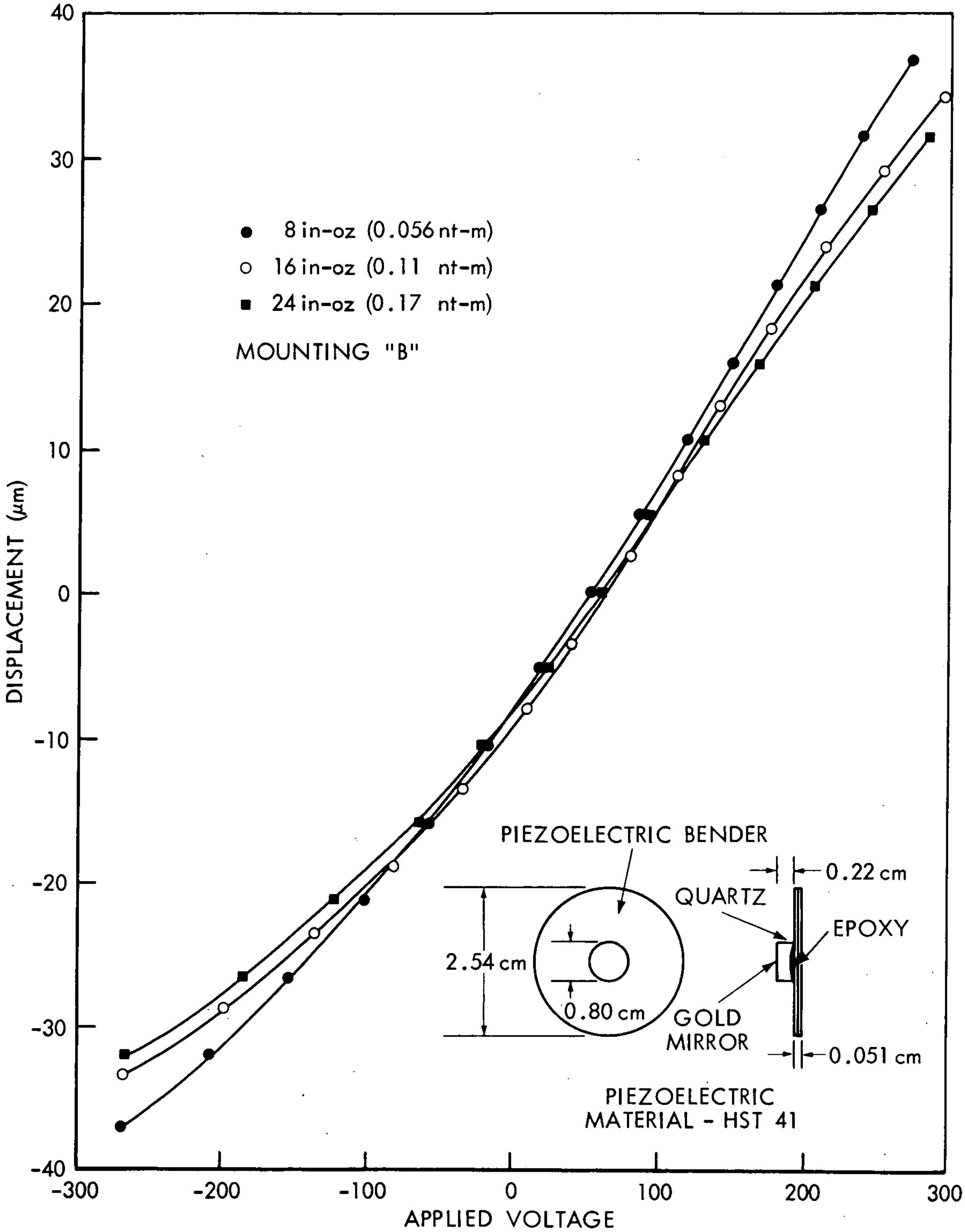

Figure 21. Experimental Results - Mounting "B"

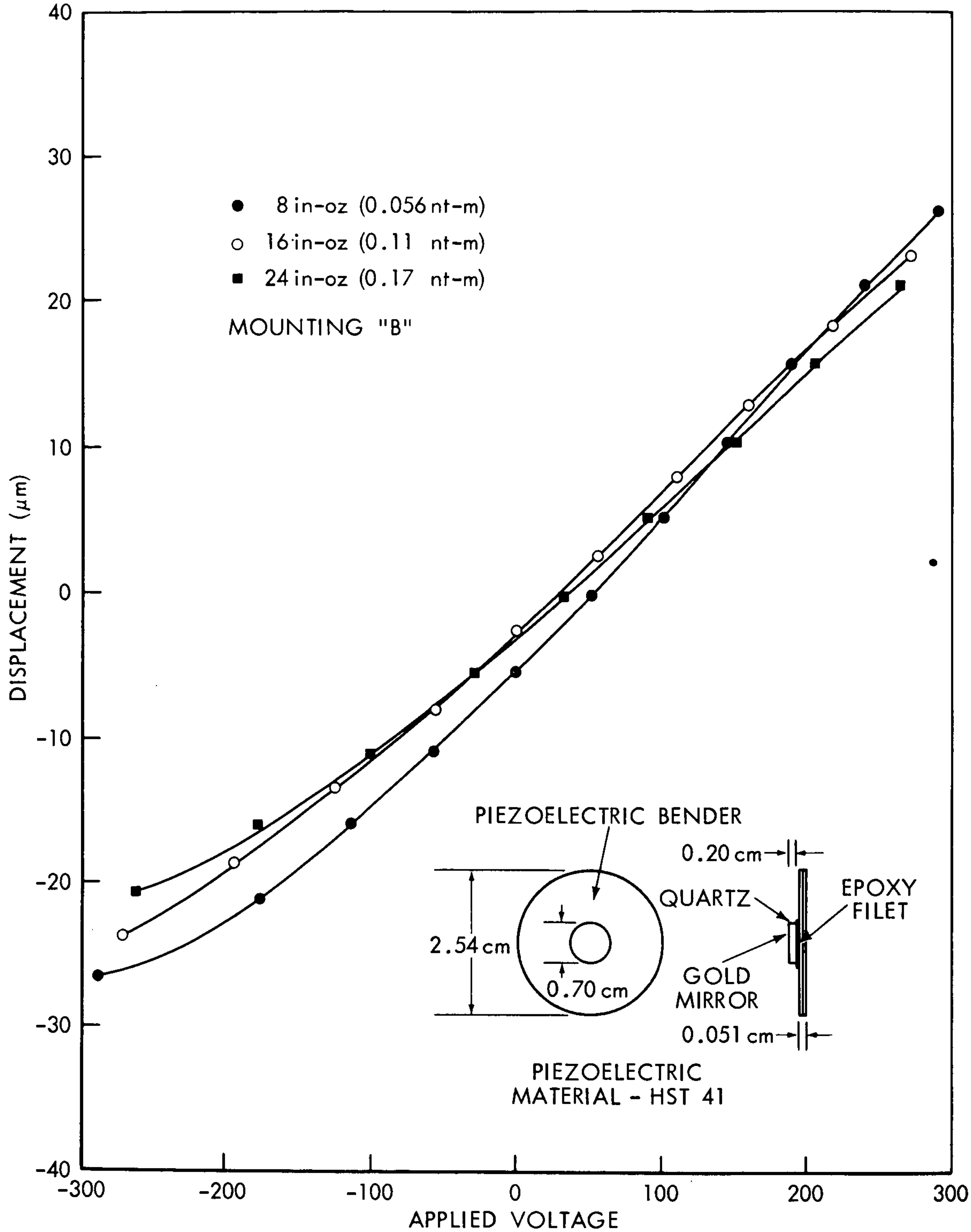

Figure 22. Experimental Results - Mounting "B"

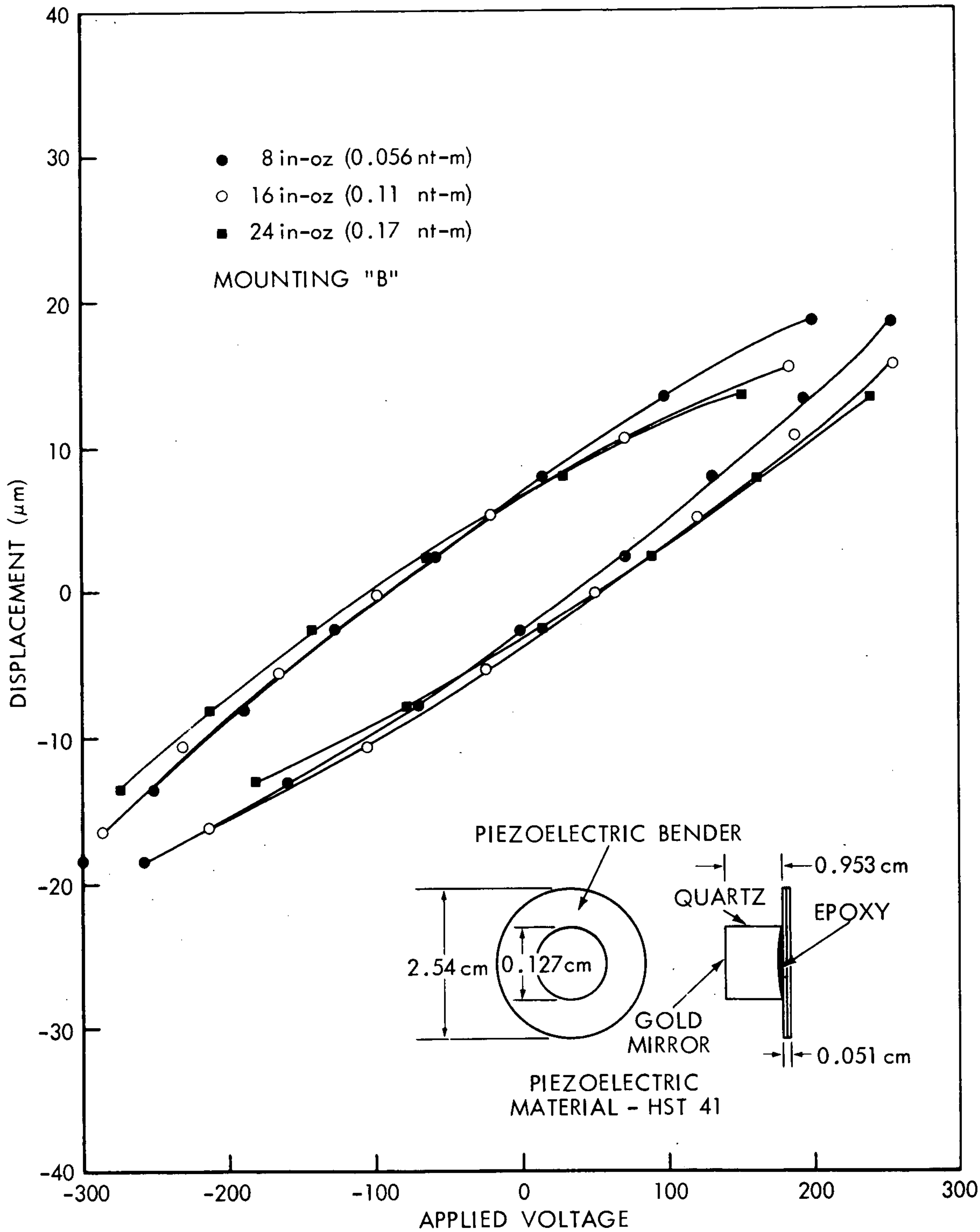

Figure 23. Experimental Results - Mounting "B"

the measurements were then repeated. It was found that the curves shown in Figures 24 and 25 were unchanged within the experimental measurement error.

In addition to the linearity, the perpendicularity of the tuner's displacement is of concern. Although this was originally anticipated to be a possible problem, it did not prove to be so in practice. The mirrors were centered on the tuners with reasonable mechanical accuracy, but without inordinate care. It was found that the laser's signature was a good indicator of the perpendicularity (with respect to the plane of the tuner) of the travel. If the laser tuner did not displace parallel to the laser's longitudinal axis, the signature would not be uniform in amplitude. The tuner mount was adjusted until the signature was uniform over the entire voltage interval; the heights of successive P(20) signals were used as a guide. When the signature was uniform it was assumed that adequate perpendicularity of travel had been obtained. This technique is depicted in Figure 26. The upper figure shows the signature of a misaligned laser and the lower figure shows that of a well aligned laser. The two signatures are for different tuner mounts so no significance should be attached to the different total displacements of the two tuners.

In Figures 15, 16, 18, and 19, theoretical curves calculated from Eq. (3) are shown. The data support the previous statement that Eq. (3) gives the nominal maximum obtainable travel, rather than the travel obtained for all mounting configurations.

3.3 Resonant Frequency Measurements

Resonant frequency measurements were also made with the set-up shown in Figure 13, but with the switch below the tuner in the opposite position. A variable-frequency sinusoidal signal was applied to the tuner and resonance was detected audibly and by observing the signature on the oscilloscope. The experimental data are shown in Figures 27 and 28 for Mountings "A" and "B", respectively. It should be noted that increasing the width of the clamping ring (solid circle through open square data points in Figure 27) has the expected effect of increasing the resonant frequency. It should also be noted that increasing the mass of the mirror has the expected effect of decreasing the resonant frequency, e.g., compare the solid triangle data to the open circle data in Figure 27 or the three curves in Figure 28.

The effect of the tuner's resonances can be quite severe in a heterodyne communication system, since a small amount of electrical pick-up coupled into the tuner at the resonant frequency can produce large instabilities in laser frequency. Figure 29 shows data taken in a heterodyne system where a beat note was obtained between two lasers and then a simulated pick-up signal was applied

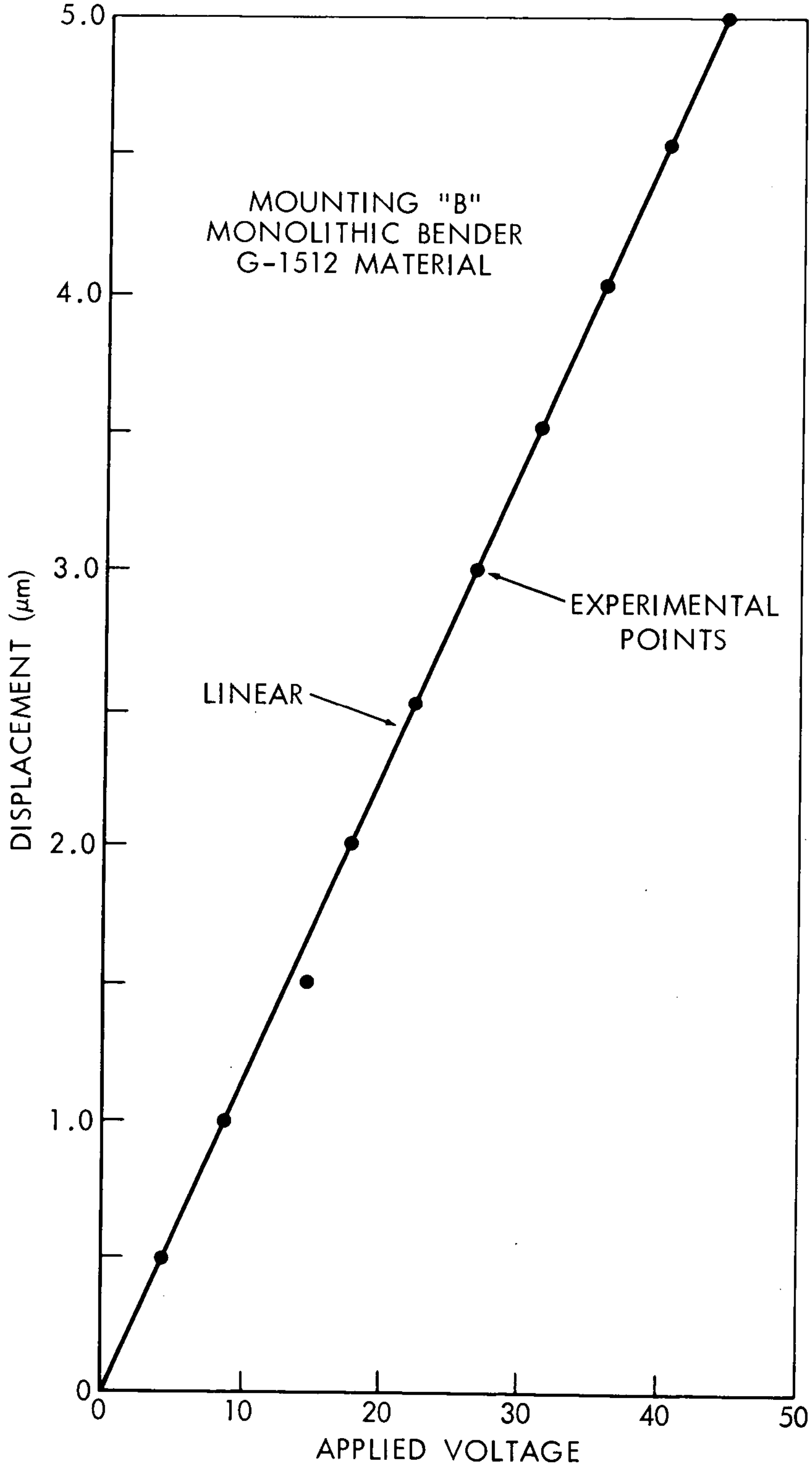

Figure 24. Mounting "B" Monolithic Bender

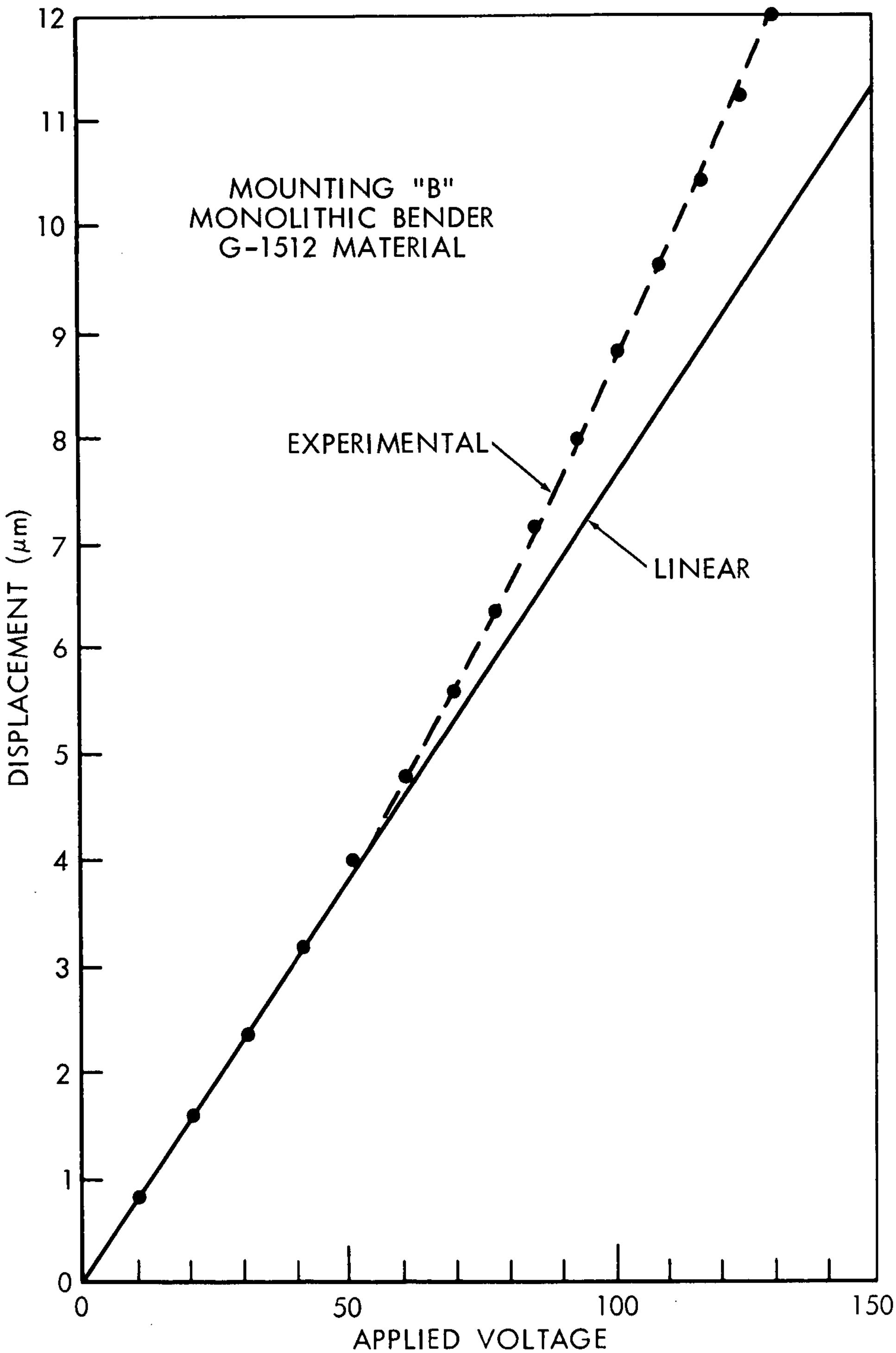

Figure 25. Mounting "B" Monolithic Bender

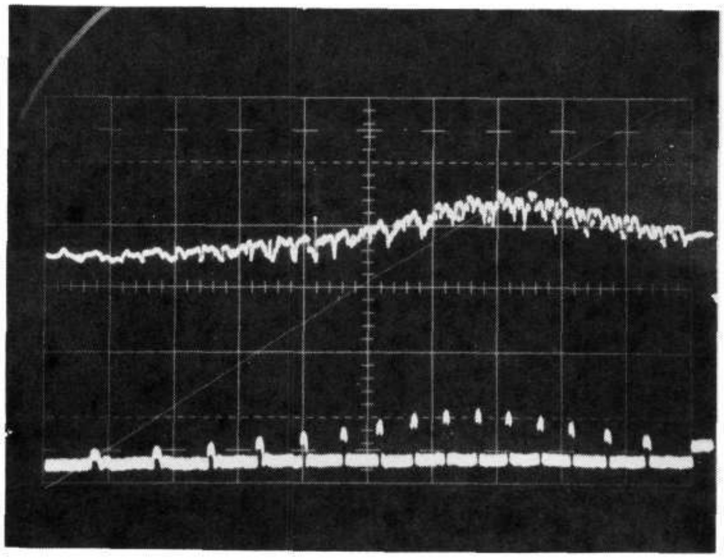

Figure 26 (a).

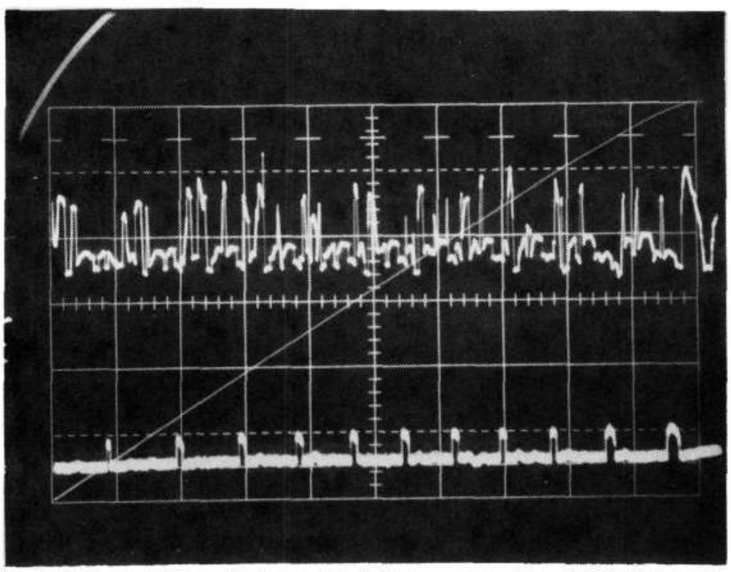

Figure 26 (b). Tuner Alignment

to the tuner of one of the lasers. It can be seen that the laser's frequency deviation per volt varies from nominally 2 MHz/volt at low frequencies to 8.45 MHz/volt at the resonant frequency of 3750 Hz.

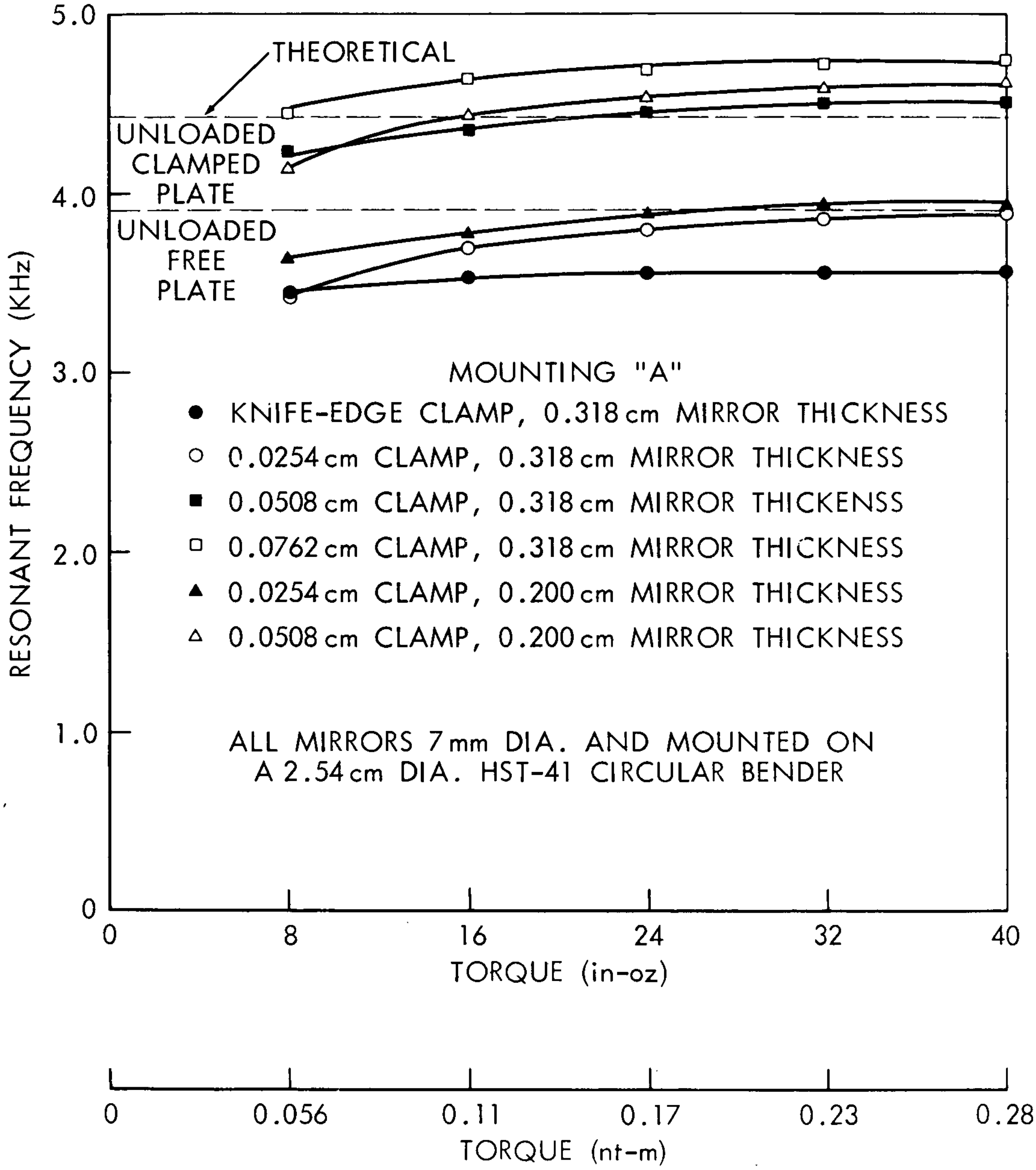

Figure 27. Experimental Data - Mounting "A"

4. CONCLUSIONS

The data presented above show that the circular piezoelectric bender is a strong competitor for laser or interferometer tuning applications where mirror diameters less than 0.5 inch (1.27 cm) are adequate and where large deflections per applied volt are required or desirable.

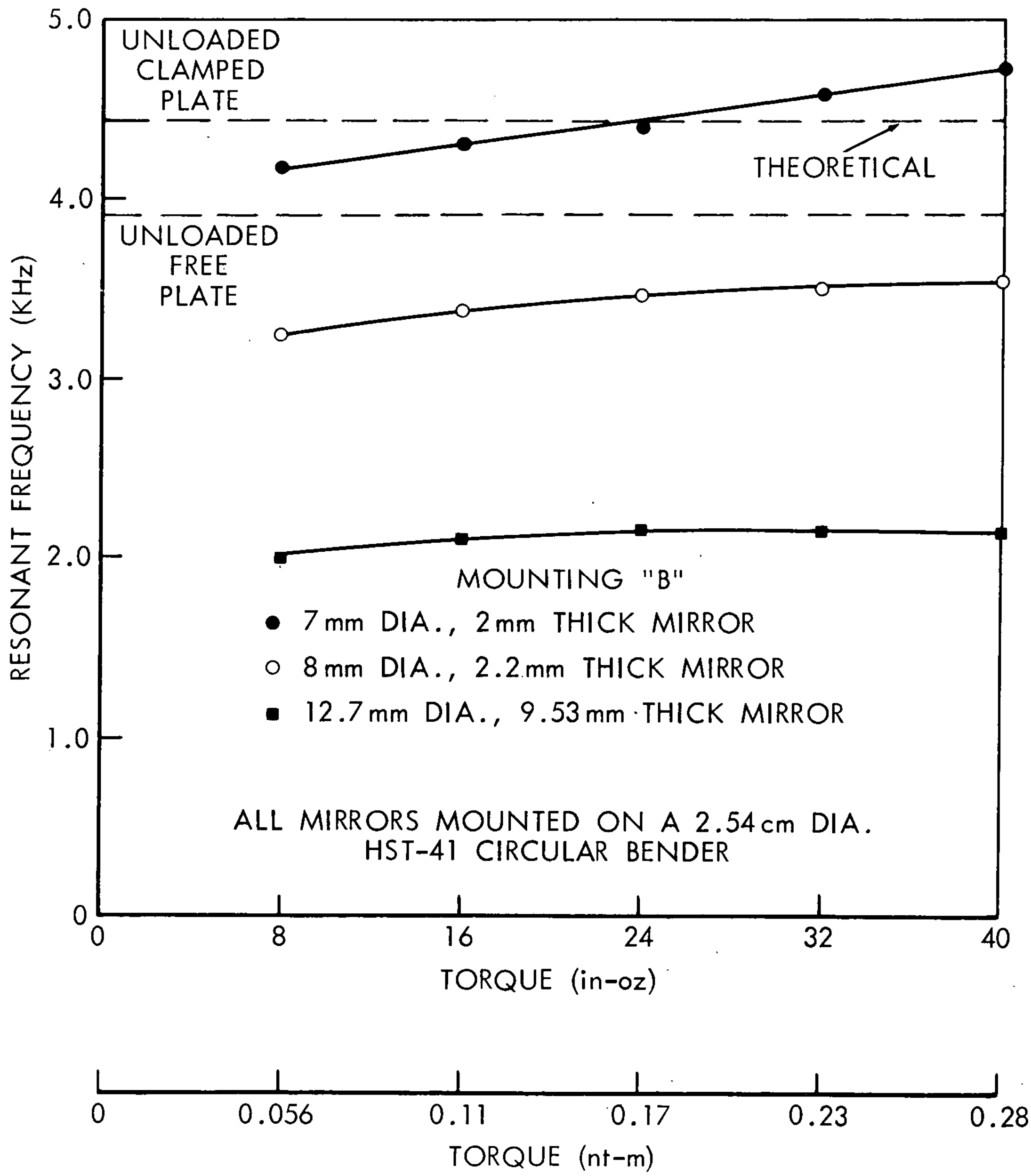

Figure 28. Experimental Data - Mounting "B"

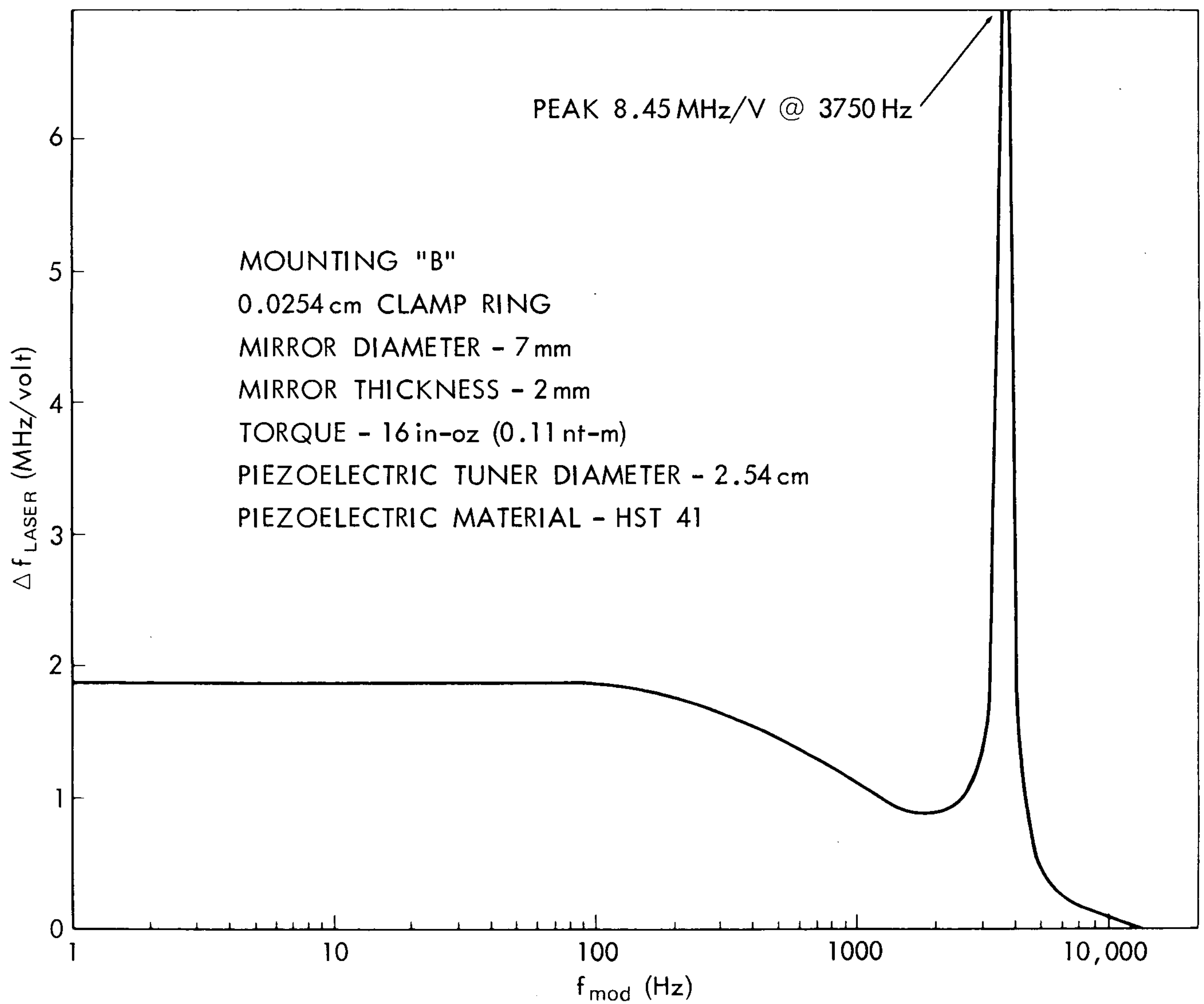

Figure 29. Data Taken in a Heterodyne System

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